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ENERGY STUDIES, SECOND EDITION

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PREFACE

The industrially developed countries of the world have become rich and prosperous by the profligate use of fossil fuels: coal, oil and natural gas. Countries of the developing areas of the world, mainly in the Pacific Rim and Far Fast, are starting to use fossil fuels, especially oil, at increasing rates. But both oil and natural gas reserves are fast depleting and are non-renewable. Each source has only a few tens of years of stock remaining. How is future world energy demand to be met?

To address such a fundamental problem, it is vitally important that all of the various elements comprising the problem are well understood. In the case of world energy, the problem elements are the individual energy sources, both old and new.

At least ten distinct types of energy source exist:

coal
oil
natural gas
nuclear
geothermal
biological/chemical
hydroelectric
wind
wave/tidal
solar energy

Each of these sources is examined in *Energy Studies*, in an attempt to take stock of the development of each, towards either depletion or viable widespread utilisation. Environmental implications, economic assessments and industrial risks are also considered.

By doing this, the authors are able to conclude with an illustrative example of an energy strategy with which to address the world energy future, so encouraging readers to weigh for themselves the complex problem which now stares mankind in the face.

Chapter 1 is written mainly for students of the physical sciences and engineering. More general readers are advised to begin reading from Chapter 2.

W. Shepherd and D. W. Shepherd
July 1997

PREFACE TO THE SECOND EDITION

In the five years that have elapsed since the original publication, the issues of energy matters and environmental concerns have become prominent. Energy supply and use is now a matter of frequent reports, not only in trade journals but in the popular press.

Up-to-date figures are now given for items of fuel supply and also for the use of renewable sources such as wind energy and photovoltaics. The chapters on geothermal energy and nuclear energy have been extended. Increased coverage is given to waste and waste disposal, in Chapter 13.

The energy strategy proposed in the first edition is unchanged. It is the view of the authors that this remains the logical, sensible and workable way to proceed.

W. Shepherd and D. W. Shepherd
June 2002

ACKNOWLEDGEMENTS

Much of the material in this book has been taught in undergraduate and postgraduate courses at the University of Bradford, England, and Ohio University, Athens, Ohio, USA. The authors are grateful to both universities for permission to reproduce teaching and examination materials.

The information was obtained from a vast number of sources, some original. Wherever possible the authors have attributed their sources. Thanks are due to the publishers of pre-existing material for their generous permission to reproduce previously published information. The authors apologise if any pre-existing material is not adequately attributed — this is not an attempt to deceive but due to inadvertence.

Dr James Brooks of Glasgow, Scotland, a distinguished geochemist, read the manuscript. His many helpful criticisms and suggestions have enhanced the presentation, especially the chapters on fossil fuels and on geothermal energy.

The authors' work was greatly helped by the superb facilities of the Alden Library at Ohio University. Special thanks are due to Lars Lutton, photographer, Samuel Girton and Scott Wagner, graphic artists, and especially to Peggy Sattler, graphic design manager in the Instructional Media and Technology Services Unit.

We are grateful to Mr Michael Mitchell of Bradford, England, for his valuable help with the computer-generated diagrams.

The typing of the manuscript, with its many revisions during the evolution, was largely done by Suzanne Vazzano of Athens, Ohio. Her professionalism and good nature were indispensable in its completion.

Athens, Ohio, USA
1997

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CHAPTER 1

ENERGY AND POWER

Energy is the capacity or capability to do work. All materials possess energy, because they can all be utilised in some form of energy conversion process. For example, most substances will burn or vaporise, and the consequent heat energy can be harnessed within mechanical energy systems that create motion against some form of mechanical resistance.

Energy can take several forms, as classified in Table 1.1. Mass or matter is a form of highly concentrated energy. Some forms of matter can be utilised in nuclear energy applications, as discussed in Chapter 8.

Table 1.1. Forms of energy.

biofuels (e.g. wood)	mass
chemical	mechanical – kinetic
electrical	mechanical – potential
gravitational	nuclear
heat (thermal)	radiation
magnetic	sound

1.1. Energy Conversion

The many applications of the use of energy usually involve transformations between different forms of energy — a process known as energy conversion. Any conversion between different energy forms is imperfect in that some of the energy has to be used to facilitate the conversion process. The converted energy output is lower than the energy input and this feature is usually described as the conversion efficiency. Figure 1.1 illustrates the large range of variation of energy conversion efficiencies, from very large electricity generators (mechanical to electrical converters) which can operate continuously at about 99% efficiency to the incandescent electric lamp (electrical to radiant converter) which is only a few percent efficient [1]. Some well-known energy conversion processes involve two successive stages. An example

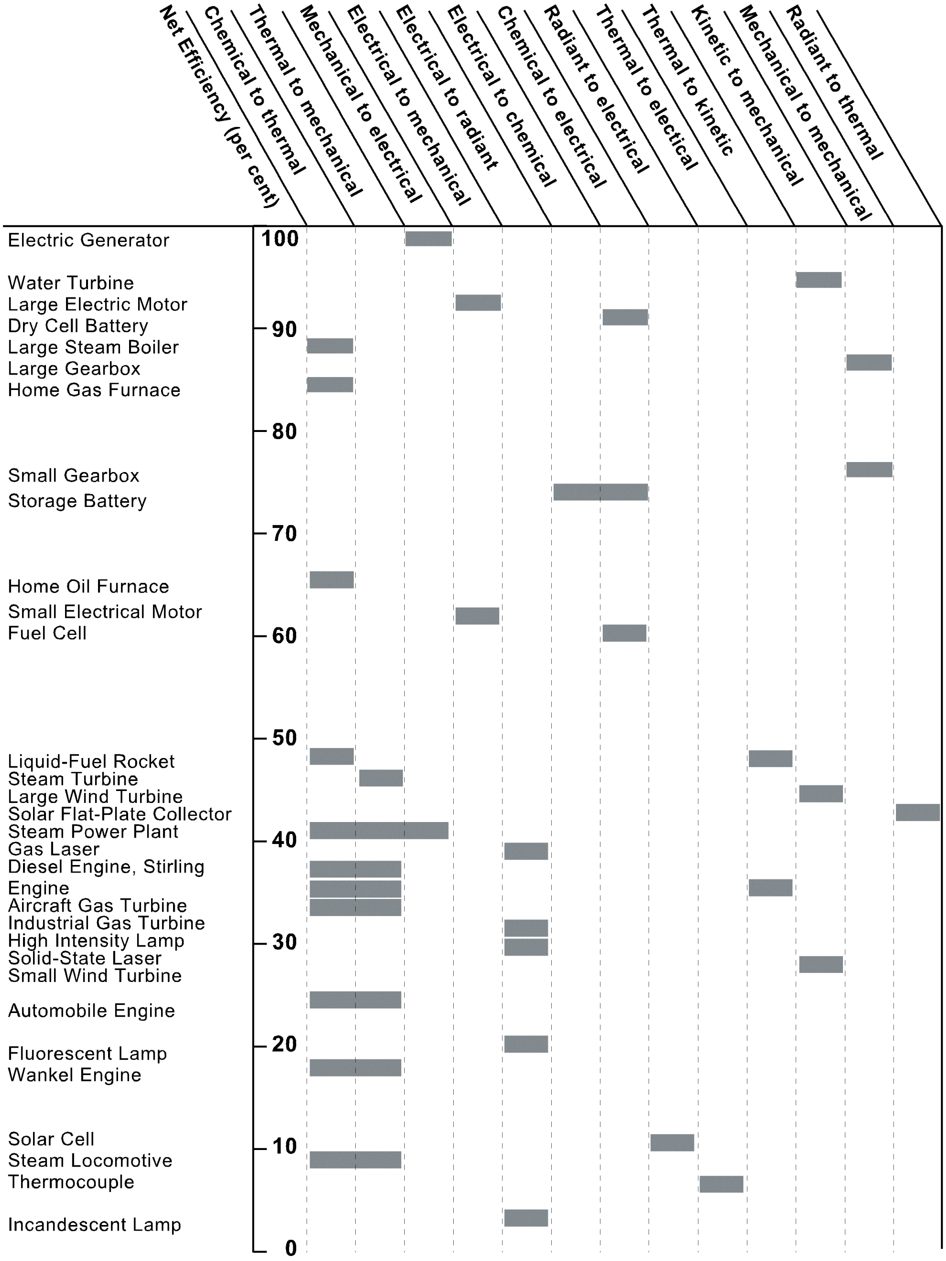


Fig. 1.1. Efficiencies of energy converters (based on [1]).

is the motor car engine in which chemical energy in the form of oil or petrol (gasoline) is converted to heat and then to rotational energy.

1.2. Mechanical Energy

The widely used Laws of Motion for bodies of constant mass were developed by the English scientist Isaac Newton in the 17th century. It is now known that in extreme cases Newton's Laws are insufficient — for very small masses quantum mechanics must be employed; with very high speeds, Einstein's theory of special relativity becomes relevant; with very large masses, the concepts of space and time are modified by the theory of general relativity. Nevertheless, for general conduct of life on earth using realistic sizes and time spans, the work of Newton remains valid.

1.2.1. *Linear motion*

When a constant force F is applied to an object and causes it to move through a distance x in the direction of the force, then the work done W is equal to the energy expended:

$$W = Fx \tag{1.1}$$

In (1.1), if the force is in newtons (N) and the distance in metres (m), the work or energy W has the unit of joules (J) or newton-metres (Nm).

If a body of mass m moves in a straight line with a linear velocity v which is the time rate of change of its position,

$$\begin{aligned} v &= \frac{dx}{dt} \text{ for small changes of } x \\ v &= \frac{x}{t} \text{ for large changes of } x \end{aligned} \tag{1.2}$$

If a body of mass m moving in a straight line is subjected to changes of velocity, the rate of change of the velocity with time is known as the acceleration a:

$$a = \frac{dv}{dt} = \frac{d}{dt}\left(\frac{dx}{dt}\right) = \frac{d^2x}{dt^2} \tag{1.3}$$

In S.I. units, mostly used in this book, the velocity is measured in metres/sec (m/s) and the acceleration in metres/sec/sec or metres/sec^2 (m/s^2).

When a force F is applied to a body of constant mass m and causes the linear velocity v to change, the resulting acceleration can be shown experimentally to be proportional to the applied force:

$$F = ma = m\frac{dv}{dt} = m\frac{d^2x}{dt^2} = mv\frac{dv}{dx} \tag{1.4}$$

Equation (1.4) is sometimes referred to as Newton's Second Law of Motion.

Mass m may be combined with velocity v to define an important physical property known as the momentum:

$$\text{Linear Momentum} = mv = m\frac{dx}{dt} \tag{1.5}$$

Comparison of (1.4) and (1.5) shows that

$$\begin{gathered} \text{Force} = \text{time rate of change of linear momentum} \\ F = m\frac{dv}{dt} = \frac{d}{dt}(mv) \end{gathered} \tag{1.6}$$

Equation (1.6) shows that momentum has the dimension of force × time or mass × velocity.

A mass m possesses energy of two kinds, known as potential energy, associated with its position, and kinetic energy, associated with its motion. The gravitational potential energy of a body of mass m, at height h above a datum plane, is given by

$$W_{\mathrm{PE}} = mgh \tag{1.7}$$

where g is the gravitational acceleration constant, of value $g = 9.81\ \mathrm{m/s^2}$. If the mass m is in kilogrammes and height h is in metres, the potential energy W_{PE} is in joules.

While a mass m is in linear motion at a constant velocity v, the kinetic energy W_{KE} associated with the motion is

$$W_{\mathrm{KE}} = \frac{1}{2}mv^2 \tag{1.8}$$

It can be seen from (1.8) that the derivative of kinetic energy W_{KE} with respect to velocity gives the momentum

$$\frac{dW_{\mathrm{KE}}}{dv} = mv \tag{1.9}$$

Both kinetic energy and momentum, like mass, satisfy important conservation rules. In this book the most relevant rule is the Principle of Conservation of Energy, which states that "in any physical system the total energy remains constant — energy may be converted to a different form, it may be wasted, but it cannot be destroyed". When a mass m in linear motion is acted upon by a force F, then, in moving between two locations:

$$\text{force} \times \begin{matrix}\text{distance}\\ \text{moved}\end{matrix} = \begin{matrix}\text{work done on}\\ \text{or against the}\\ \text{mass}\end{matrix} = \begin{matrix}\text{change of kinetic}\\ \text{energy between}\\ \text{the two locations}\end{matrix} \tag{1.10}$$

Example 1.1

A mass m initially rests on a ledge at height h metres above ground level, which is the datum plane. Define the conditions of velocity, kinetic energy and potential energy (i) initially, (ii) as the mass falls to ground, (ii) finally after the mass comes to rest.

(i) With the mass at rest, its initial velocity v_i is zero and therefore so are its initial momentum and kinetic energy. Its total energy is then the potential energy given by (1.7), illustrated in Fig. 1.2.

(ii) As the mass falls to the ground it possesses an instantaneous velocity v', initially zero and increasing uniformly due to gravitational acceleration. Its final velocity becomes zero on impact with the ground. At any arbitrary height h' during the fall, the mass possesses both potential energy mgh' and kinetic energy $\frac{1}{2}mv'^2$, which sum to the initial energy mgh. After striking the ground the final velocity v_f is zero, the momentum of the motion is transferred to the ground and the kinetic energy is converted to local heat and sound due to impact. Since the ground level is the datum plane, the potential energy after impact is also zero here.

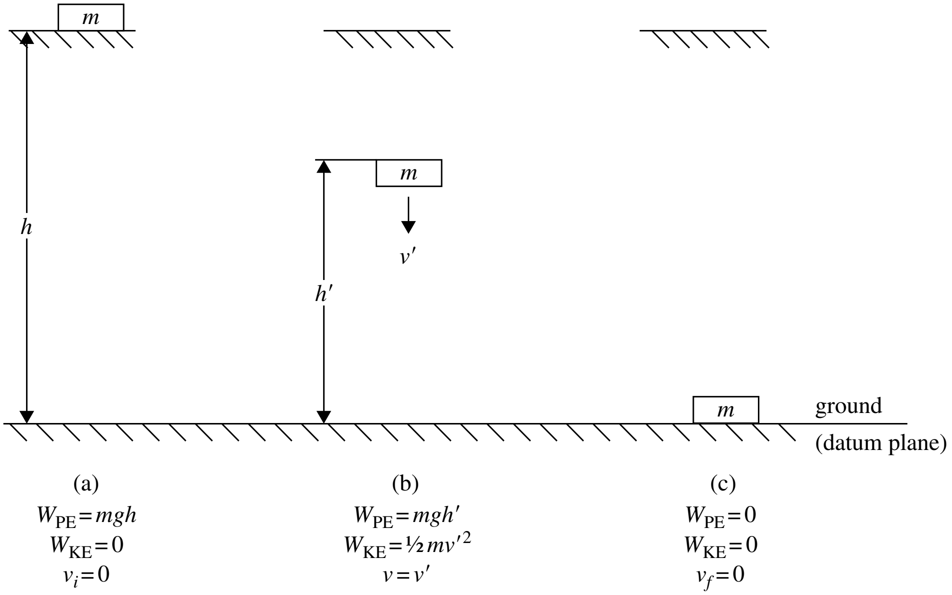


Fig. 1.2. Mass falling freely under gravity.

1.2.2. *Rotational motion*

Most energy conversion processes involving mechanical energy incorporate rotational devices. For example, electromechanical energy converters use rotors that have the form of solid cylinders, Fig. 1.3(a). Petrol engines and diesel engines usually incorporate flywheels, Fig. 1.3(b). The rotor of a water or gas turbine also has the nature of a non-uniform flywheel.

To illustrate some of the principles of rotational motion, the example used is that of a concentrated mass m in circular motion at radius r about a fixed centre point, Fig. 1.4. The motion is characterised by the angular velocity $\boldsymbol{\omega}$ in radians/sec (rad/s) and the instantaneous tangential velocity v of the mass in metres/sec (m/s), where

$$v = \boldsymbol{\omega} r \tag{1.11}$$

A centripetal force acting radially inwards is required to keep the mass moving in a circle and is provided along the tie rod. With rotational motion, the externally applied force F acting tangentially on the mass (through a rigid tie-rod), Fig. 1.4, times the radius r is called the torque T, which acts as a rotation producing force:

$$T = Fr = F\frac{v}{\boldsymbol{\omega}} \tag{1.12}$$

Torque is measured in newton-metres (Nm) and is a very important property of rotating energy converters. The tangential or linear acceleration of the mass m is given, from (1.11), by

$$a = \frac{dv}{dt} = r\frac{d\boldsymbol{\omega}}{dt} \tag{1.13}$$

Combining (1.12) and (1.13) leads to

$$\begin{aligned} T &= Fr \\ &= mar \\ &= m\frac{dv}{dt}r \\ \therefore T &= mr^2\frac{d\boldsymbol{\omega}}{dt} = mr^2\boldsymbol{\alpha} \end{aligned} \tag{1.14}$$

In (1.14) the term α is the angular acceleration in rad/s^2. The quantity mr^2 in (1.14) is known as the polar moment of inertia J and is an important physical property in rotational structures, having the dimension kgm^2.

$$J = mr^2 = [\text{mass}]\ [\text{radius of gyration}]^2 \tag{1.15}$$

Expression (1.15) is true directly for the flywheel and cylinder of Fig. 1.3. For more complicated structures with distributed, non-uniform mass, the effective radius of gyration is more complicated but the relationship (1.15) is still valid in principle.

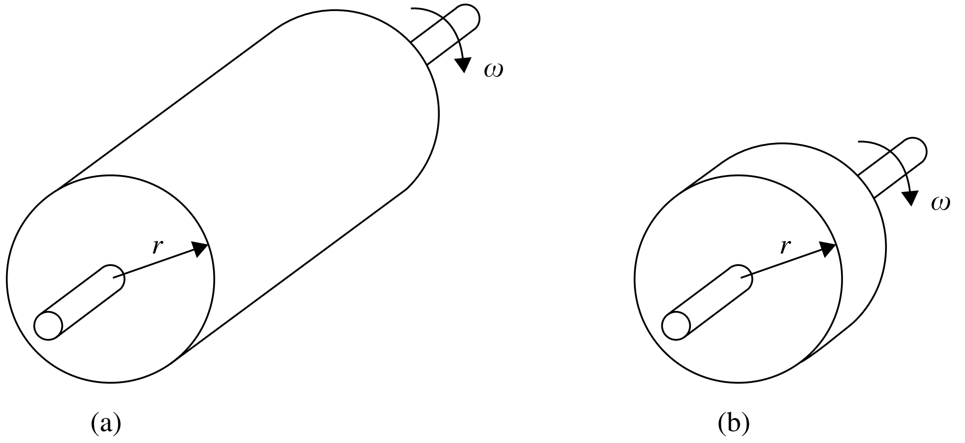


Fig. 1.3. Structure of some mechanical energy converters. (a) Electric motor or generator (b) Flywheel (internal combustion engine).

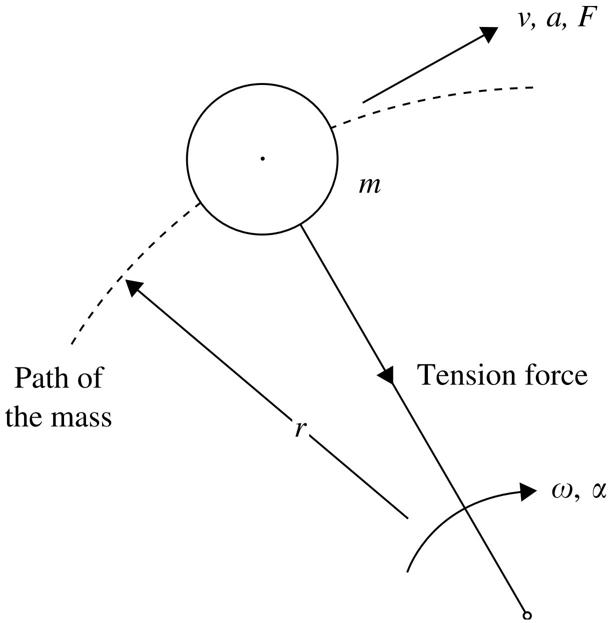

v, a, F
m
Path of the mass
Tension force
r
ω, α

Fig. 1.4. Mass rotating in a horizontal circle.

The properties of (1.14) and (1.15) can be summarised as

$$T = J\boldsymbol{\alpha} = J\frac{d\boldsymbol{\omega}}{dt} \tag{1.16}$$

which is directly analogous to (1.14) for linear motion.

The kinetic energy associated with rotational motion can be obtained by incorporating (1.11) into (1.8), using (1.15):

$$\begin{aligned} W_{\mathrm{KE}} &= \frac{1}{2}mv^2 \\ &= \frac{1}{2}mr^2\boldsymbol{\omega}^2 \\ \therefore W_{\mathrm{KE}} &= \frac{1}{2}J\boldsymbol{\omega}^2 \end{aligned} \tag{1.17}$$

When J is in kgm^2 and $\boldsymbol{\omega}$ in rad/s, the energy of motion, which is also the work done on the rotating mass, has the dimension of joules (J) or watt-seconds (Ws).

Example 1.2

A solid mass m rotates around a fixed centre point at radius r with constant angular velocity $\boldsymbol{\omega}$. Show that the force F which impels the motion is proportional to the time rate of change of angular momentum.

In Fig. 1.4 the tangential force which causes the rotation and maintains it is given by

$$\begin{aligned} F &= ma \\ &= m\frac{dv}{dt} \end{aligned}$$

For constant mass, therefore,

$$\begin{aligned} F &= \frac{d}{dt}(mv) \\ &= \text{time rate of change tangential momentum}, mv \\ &= \frac{d}{dt}(m\boldsymbol{\omega}r) = r\frac{d}{dt}(m\boldsymbol{\omega}) \\ &= [r]\ [\text{time rate of change of angular momentum}] \end{aligned}$$

Example 1.3

The rotor of an electric motor has a polar moment of inertia of 10 kgm^2 and rotates at a steady speed of 1800 revolutions per minute (rpm). Calculate the kinetic energy of the motion.

J = 10 kgm^2.
The angular velocity is given in rpm and must be converted to the corresponding S.I. unit of radians/sec.

$$\begin{aligned} 1800 \text{ rpm} &= \frac{1800}{60} \text{ rev/s} \\ &= \frac{1800}{60}\, 2\boldsymbol{\pi} \text{ rad/s} \\ &= 6\boldsymbol{\pi} \text{ rad/s} \end{aligned}$$

The kinetic energy, from (1.17), is

$$\begin{aligned} W_{\mathrm{KE}} &= \frac{1}{2} J \boldsymbol{\omega}^2 \\ &= \frac{1}{2} 10 (6\pi)^2 \\ &= 2418 \text{ joules} \end{aligned}$$

This value also represents the work that was done in rotating the motor from rest to its steady speed.

1.3. Electrical Energy

Electrical energy is the universal clean form of energy that is most used. It is, however, a secondary form of energy that has to be obtained by the use of a primary fuel such as coal or oil. Because of the great importance of electrical energy it is the subject of a separate section, in Chapter 3.

1.4. Chemical Energy

Chemical energy may be associated with chemical reactions, combustion engines, rockets, electrical cells and batteries, heating from boilers, etc. The energy is usually stored within materials and is released by combustion. Some aspects of chemical energy storage are covered in Chapter 7.

1.5. Nuclear Energy

The energy stored within an atomic nucleus is manifested, for certain chemical elements, by radioactive decay. Energy can be made available by the processes of nuclear fission and nuclear fusion, discussed in Chapter 8.

1.6. Thermal Energy

Heat (thermal) energy is so important a feature of energy conversion systems and incorporates so many vital physical principles that it is treated in a major section immediately below.

1.7. Thermodynamics and Heat Energy

1.7.1. *Quantity of heat*

Heat is a form of energy. It has the capacity to do work directly as thermal warming or by conversion to other energy forms, mainly mechanical. The quantity of heat involved in a process can be measured by some effect which accompanies the process. Traditional units of measurement for the quantity of heat Q are the calorie (in cgs units) and the British thermal unit or BTU (fps units).

1 calorie is the amount of heat to raise 1 gramme (1 g) of water through 1°C.
1 BTU is the amount of heat to raise 1 pound (1 lb) of water through 1°F.

Note that heat is not the same as temperature. The quantity of heat Q is a measure of the energy capacity whereas temperature T is a measure of the hotness.

The amount of heat energy required to raise the temperature of a particular mass of material through a specified temperature range is a characteristic property of the material. In particular, the specific heat capacity is the heat capacity per unit mass, and is measured in cals/g-centigrade or BTU/lb-fahrenheit. Water is the standard material, having a specific heat capacity of 1 cal/g°C or 1000 cals/kg°C or 1 BTU/lb°F. It is common to use a dimensionless property known as specific heat (SH),

$$SH = \frac{\text{specific heat capacity of a material}}{\text{specific heat capacity of water}} \tag{1.18}$$

Water, therefore, has the value $SH = 1$.

A mass m of material raised through a temperature difference $(T_2 - T_1)$ possesses a quantity of heat energy Q where

$$\begin{aligned} Q &= [\text{heat capacity of the body}] \times [\text{temperature difference}] \\ &\text{or} \\ Q &= mSH(T_2 - T_1) \end{aligned} \tag{1.19}$$

In (1.19), Q has the dimension of mass × temperature.

1.7.2. *Mechanical equivalent of heat*

Mechanical energy is expressed in units of ergs (cgs system), ft lb (fps system) or joules (S.I. system). The equivalence between mechanical energy units and heat energy has to be determined by experiment. This equivalence has the internationally agreed value, formerly known as the "mechanical equivalent of heat",

$$1 \text{ g-calorie} \equiv 4.186 \text{ joules}$$

$$1 \text{ BTU} \equiv 7718.26 \text{ ft lb}$$

$$\equiv 252 \text{ g-cal}$$

$$\equiv 1054.7 \text{ joules}$$

Slight approximation of the above figures is often permitted so that the energy or work W in joules is given by

$$\begin{aligned} W &= 4.2Q \qquad \text{if } Q \text{ is in calories} \\ &= 1055Q \quad \text{if } Q \text{ is in BTUs} \end{aligned} \tag{1.20}$$

A well-known energy conversion process incorporating a heat-to-work stage is electricity generation, illustrated in Fig. 1.5. Chemical energy in the solid fuel is released by combustion and used to boil water in a closed-cycle system that is thermally insulated to reduce heat loss. Energy in the form of pressurised steam rotates the blades of a steam turbine. After imparting much of its energy to the turbine, the steam condenses back into hot water that needs to be force-cooled from some large external source of cooling water such as a sea, lake or river. Rotational mechanical energy is transferred from the turbine to the electric generator. A more detailed consideration of electricity generation is given in Chapter 3.

The conversion of heat energy into mechanical work also takes place in petrol engines, diesel engines, jet engines, gas turbines and rocket motors. These may all be grouped under the title of "heat engines". Energy conversion of this form is restricted in scope and efficiency by certain natural laws and limitations embodied in a formulation called the laws of thermodynamics.

1.7.3. ***The first law of thermodynamics***

When the Principle of Conservation of Energy is applied to a heat–work conversion process, it becomes known as the first law of thermodynamics and can be stated thus:

> *In an isolated, enclosed heat–work system the total energy remains constant.*

An expanded statement of the first law is

> *The change of internal energy of a system is equal to the net heat energy input (Q) minus the net external work done (W).*

In equation form

$$\begin{matrix}\text{net heat energy} \\ \text{supplied}\end{matrix} - \begin{matrix}\text{net work done by} \\ \text{the system}\end{matrix} = \begin{matrix}\text{change in} \\ \text{stored energy}\end{matrix}$$

or

$$Q - W = \begin{matrix}\text{final stored} \\ \text{energy}\end{matrix} - \begin{matrix}\text{initial stored} \\ \text{energy}\end{matrix} \tag{1.21}$$

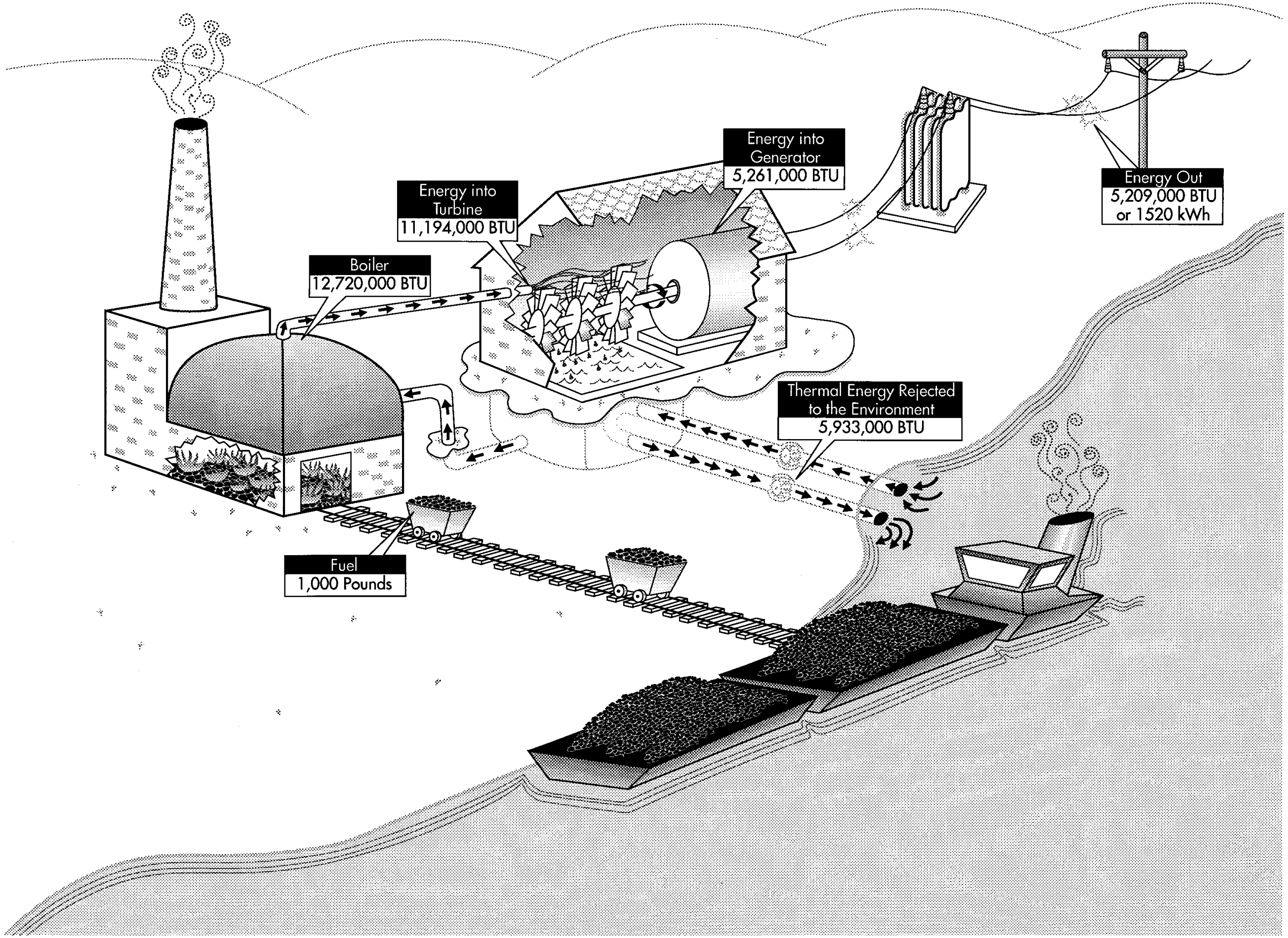

Energy into
Generator
5,261,000 BTU
Energy Out
5,209,000 BTU
or 1520 kWh
Energy into
Turbine
11,194,000 BTU
Boiler
12,720,000 BTU
Thermal Energy Rejected
to the Environment
5,933,000 BTU
Fuel
1,000 Pounds

Fig. 1.5. Basic form of a heat–work system for electricity generation (based on an idea in Dorf [2]).

Even if the operating level of the system changes (e.g. it operates at say a higher level of heat input and consequent higher work done), the quantity $(Q - W)$ remains constant. The first law states, in effect, that not more than 4.186 joules of mechanical energy can be obtained from 1 g-calorie of suitably heated material irrespective of the energy conversion process. It is significant that the first law does not describe any changes that may occur in the quality of the stored energy nor in its capacity to do work.

1.7.4. *The second law of thermodynamics*

The heat energy contained within a body varies directly with its temperature, as implied in (1.19). The process of cooling implies a reduction of energy. Heat always flows spontaneously from a body of higher temperature to a body of lower temperature in an attempt to obtain a thermal energy equilibrium of uniform temperature. There can be no spontaneous flow of heat energy from a cooler body to a hotter body — this would be analogous to water spontaneously flowing uphill.

A heat transfer process is always imperfect. However well the system is designed and maintained, some heat is lost to the surroundings in the form of exhaust gases, cooling liquids or gases, conduction losses due to a temperature rise in pipes, convection to the ambient air, radiation into the surrounding space, etc.

1.7.4.1. *Ideal heat engine*

Even in an ideal heat engine containing no losses or design imperfections, there would still remain an important natural limitation of scope. This is expressed in one of several possible formulations of the important physical principle known as the second law of thermodynamics:

> *A cyclic heat–work operation needs to contain two thermal reservoirs. Even an ideal heat engine is capable of converting only part of the input heat energy into work. The remaining heat energy must be transferred to a lower temperature reservoir.*

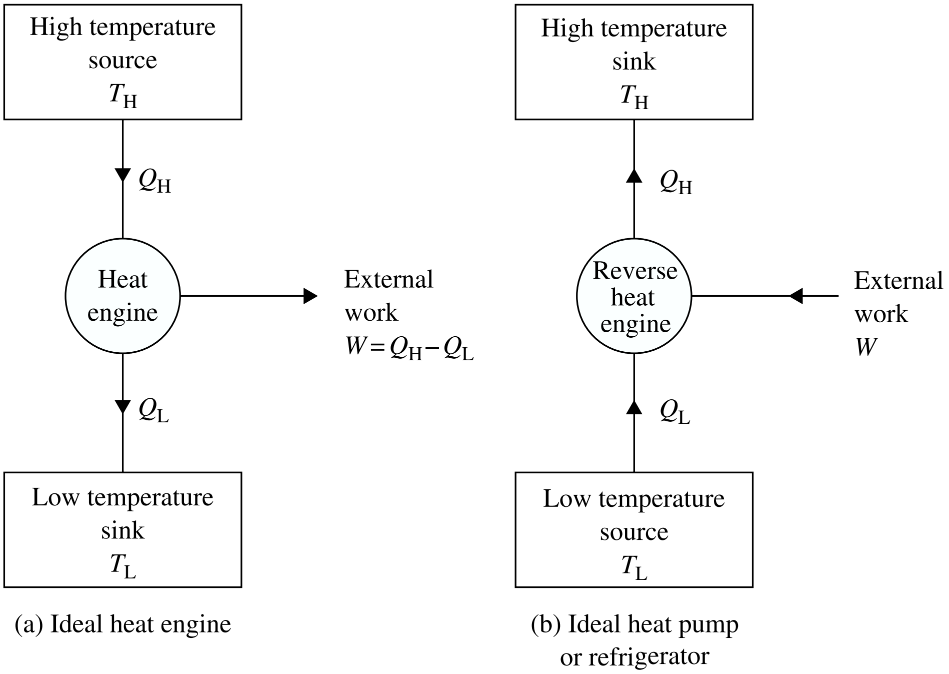
The first and second laws of thermodynamics are illustrated by application to an ideal heat engine in Fig. 1.6.

If there is no stored energy, then from the first law statement of (1.21),

$$Q_{\mathrm{H}} - Q_{\mathrm{L}} = W \tag{1.22}$$

Now, the energy efficiency of any converter is the ratio of the energy output to the energy input. In the case of a heat–work converter the output energy is equal to the mechanical work done:

$$\boldsymbol{\eta} = \frac{\text{work output}}{\text{work input}} = \frac{W}{Q_{\mathrm{H}}} = 1 - \frac{Q_{\mathrm{L}}}{Q_{\mathrm{H}}} \tag{1.23}$$


High temperature source T_H
Q_H
Heat engine
External work $W = Q_H - Q_L$
Q_L
Low temperature sink T_L
High temperature sink T_H
Q_H
Reverse heat engine
External work W
Q_L
Low temperature source T_L

(a) Ideal heat engine

(b) Ideal heat pump or refrigerator

Fig. 1.6. Schematic function of an ideal heat engine.

It can be seen from (1.23) and Fig. 1.6(a) that the most efficient heat engine will be a form in which Q_H and T_H are as high as possible and Q_L and T_L are as low as possible. But it is important to note that Q_L and T_L cannot be reduced to zero, which would represent 100% efficiency. Cyclic interchange between Q_H and W in Fig. 1.6(a), with $Q_L = 0$, would then constitute a form of perpetual motion machine which the laws of thermodynamics declare to be impossible.

In 1824 a young French engineer called Sadi Carnot deduced that an ideal heat engine would have a theoretical maximum efficiency that has come to be known as the Carnot efficiency, η_{Carn},

$$\eta_{\text{Carn}} = 1 - \frac{T_L}{T_H} \tag{1.24}$$

In (1.24), T_L and T_H are absolute temperatures measured from the absolute minimum temperature −273°C, in units known as Kelvin (K). The two expressions, (1.23) and (1.24), can be linked via the property of entropy, which is discussed in Sec. 1.8 below.

1.7.4.2. *Practical heat engine*

A practical form of heat engine does not realise a working efficiency anywhere near to the level of the Carnot efficiency. The efficiency diagram of Fig. 1.1 shows that automobile petrol engines have working efficiencies of about 25%, diesel engines and gas turbines about 35% and steam turbines about 45%. This means that a lot of energy is wasted (not destroyed!) and a lot of thermal pollution is created. The most efficient engines only achieve a practical efficiency about two-thirds that of the Carnot efficiency.

The various energy utilisation features of a solid-fuel electricity generation plant, referred to in Sec. 1.7.2 above, are illustrated in Fig. 1.5. The energy into the turbine, 11,194,000 BTU, corresponds to Q_{H} in Fig. 1.6(a), but only 5,261,000 BTU is converted to mechanical work W. The remaining heat, 5,933,000 BTU, corresponds to Q_{L}. This heat energy is dissipated to the environment, causing increased temperature of the coolant source water. In a steam engine the low temperature sink is often referred to as a condenser.

1.7.4.3. *Ideal reverse heat engine*

If external work is done on the engine (instead of by it), heat energy can be extracted from the low temperature source and injected into the high temperature reservoir, Fig. 1.6(b). The best-known example of this is the domestic refrigerator, Fig. 1.7, in which heat is extracted from the food inside and expelled into the kitchen. In a refrigerator the reverse heat engine converts the electrical (or gas) input energy into thermal energy. The refrigerator mechanism of pump, coolant pipes and coolant chemical (liquid or gas) acts as a heat pump.

In an ideal reverse heat engine, Fig. 1.6(b),

$$Q_{\mathrm{H}} = W + Q_{\mathrm{L}} \tag{1.25}$$

In the refrigerator of Fig. 1.7 heat energy is extracted from the refrigerator contents at a time rate dQ_{L}/dt. Additional energy enters from the electrical supply at a time rate P and energy is expelled into the surroundings at a rate dQ_{H}/dt. The conservation law (1.25) is satisfied by a time rate equation

$$\frac{dQ_{\mathrm{H}}}{dt} - \frac{dQ_{\mathrm{L}}}{dt} = \frac{dW}{dt} = P \tag{1.26}$$

For any ideal heat engine or reverse heat engine, it can be shown that (1.32) below is true. Combining (1.26) and (1.32) gives a relationship for the necessary input power P in terms of temperatures:

$$P \geq \frac{dQ_{\mathrm{L}}}{dt}\left[\frac{T_{\mathrm{H}}}{T_{\mathrm{L}}} - 1\right] \tag{1.27}$$

Equation (1.27) is true for all refrigerator systems regardless of their size or mode of operation [3].

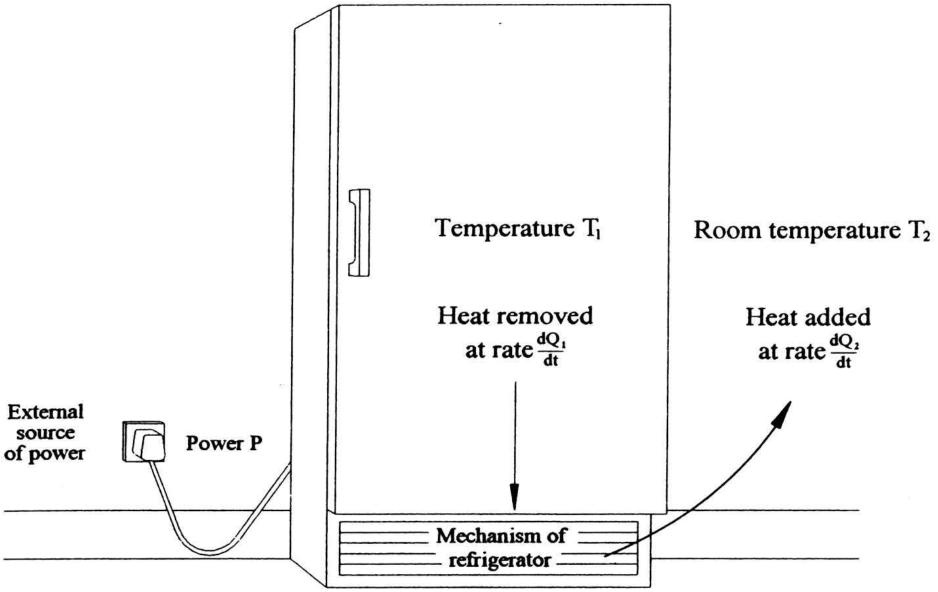

Temperature T_1
Room temperature T_2
Heat removed at rate $\frac{dQ_1}{dt}$
Heat added at rate $\frac{dQ_2}{dt}$
External source of power
Power P
Mechanism of refrigerator

Fig. 1.7. Thermal action of a refrigerator [3].

1.7.5. *Worked examples on thermodynamics and heat energy*

Example 1.4

A mass of material m_1 of specific heat SH_1, at temperature T_1, is mixed with a mass of fluid m_2 of specific heat SH_2 at temperature T_2. Express the final temperature of the mixture in terms of its constituent parts.

Let the final temperature of the mixture be T_f.
Assume that $T_1 > T_2$, so that $T_2 \leq T_f \leq T_1$.
Heat lost by mass m_1 is

$$Q_1 = m_1 SH_1 (T_1 - T_f) \tag{a}$$

Heat gained by mass m_2 is

$$Q_2 = m_2 SH_2 (T_2 - T_f) \tag{b}$$

Assuming that the mixing is thermally ideal and no heat is lost, then

$$Q_1 = Q_2 \tag{c}$$

Combining (a), (b) and (c) gives

$$T_f = \frac{m_1 SH_1 T_1 + m_2 SH_2 T_2}{m_1 SH_1 + m_2 SH_2}$$

Example 1.5

In the steam boiler–electrical plant of Fig. 1.5, what are the mechanical and electrical equivalents of the thermal energy imparted to the cooling water?

$$\begin{array}{c}\text{Thermal energy rejected}\\ \text{into the coolant water}\end{array} = Q = 5933000 \text{ BTU}$$

From (1.20),

$$\begin{aligned} W &= 1055\,Q \\ \begin{array}{c}\text{Mechanical energy equivalent}\\ \text{of the thermal energy}\end{array} &= 1055 \times 5933000 \\ &= 6259 \text{ MJ} \end{aligned}$$

Now 1 joule = 1 watt second, so that

$$\begin{aligned} \begin{array}{c}\text{Electrical energy equivalent}\\ \text{of the thermal energy}\end{array} &= 6259 \text{ MWs} \\ &= \frac{6259}{3600} \\ &= 1.739 \text{ MWh} \end{aligned}$$

Example 1.6

A thermal system has an initial internal energy of 50 kJ. Net work is done on the system of energy value 100 kJ, after which the final internal energy is found to be 75 kJ. Calculate the net heat transfer to the system.

From (1.21), for a lossless system,

$$Q - W = \text{final stored energy} \text{ — } \text{initial stored energy}$$

$$Q - W = 75 - 50 = 25 \text{ kJ}$$

Now, in (1.21), the term W represents work done by the system. In the present case work is done *on* the system (i.e. W is an energy input) and therefore

$$W = -100 \text{ kJ}$$

$$Q - (-100) = 25 \text{ kJ}$$

$$Q = 25 - 100 = -75 \text{ kJ}$$

In order to achieve a new energy balance, according to the Principle of Conservation of Energy, the heat transfer is negative (i.e. heat energy must have been removed from the system).

Example 1.7

A high temperature fluid at 600°C is transferred via a mechanical work converter to a lower temperature (condenser) sink at 100°C. If the fluid has an initial heat energy of 250 MJ, (a) what is the maximum theoretical efficiency of mechanical conversion, and (b) what is the maximum theoretical work output?

$$T_{\mathrm{H}} = 600°\mathrm{C} = 600 + 273 = 873\ \mathrm{K}$$

$$T_{\mathrm{L}} = 100°\mathrm{C} = 100 + 273 = 373\ \mathrm{K}$$

(a) The maximum or Carnot efficiency of mechanical conversion is, from (1.24),

$$\begin{aligned}\boldsymbol{\eta}_{\mathrm{Carn}} &= 1 - \frac{T_{\mathrm{L}}}{T_{\mathrm{H}}} \\ &= 1 - \frac{373}{873} \\ &= 1 - 0.427 = 0.573 \text{ or } 57.3\%\end{aligned}$$

(b) From (1.23),

$$\boldsymbol{\eta} = \frac{W}{Q_{\mathrm{H}}}$$

so that

$$\begin{aligned}W &= \boldsymbol{\eta} Q_{\mathrm{H}} \\ &= 0.573 \times 250 = 143.25\ \mathrm{MJ}\end{aligned}$$

Example 1.8

A domestic refrigerator has a freezer compartment with its temperature set at 20°F. The room temperature is 70°F. What is the minimum external energy input requirement if it takes 40 kcal of heat extraction to freeze a tray of ice cubes?

Since zero Kelvin = −273.15°C,

$$T_{\mathrm{H}} = 70°\mathrm{F} = 21.1°\mathrm{C} = 294.25\ \mathrm{K}$$

$$T_{\mathrm{L}} = 20°\mathrm{F} = -6.7°\mathrm{C} = 266.3\ \mathrm{K}$$

$$Q_{\mathrm{L}} = 40\ \mathrm{kcal} \equiv 40 \times 4.18 = 167.2\ \mathrm{kJ}$$

Integrating both sides of (1.27),

$$\int P dt \geq \int dQ_{\mathrm{L}} \left[\frac{T_{\mathrm{H}}}{T_{\mathrm{L}}} - 1\right]$$

$$W_{\mathrm{in}} = Pt \geq Q_{\mathrm{L}} \left[\frac{T_{\mathrm{H}}}{T_{\mathrm{L}}} - 1\right]$$

$$\begin{aligned} W_{\text{in}} &\geq 167.2\left[\frac{294.25}{266.3} - 1\right] \text{ kJ} \\ &\geq 167.2[1.105 - 1] \text{ kJ} \\ &\geq 17.56 \text{ kJ} = 17.56 \text{ kWs} \end{aligned}$$

The total "load" on the refrigerator, to freeze the freezer compartment and to cool the main space, is many times the above value.

The rate of heat extraction from a freezer compartment is likely to be of the order 1–3 kcal/min. If this machine extracts heat at (say) 2 kcal/min, it will take 17.52/2 or 8.76 min to freeze the water.

1.8. Entropy

1.8.1. *Entropy in heat–work systems*

The second law of thermodynamics has basic and profound scientific implications far beyond that of heat–work interchange in heat engines. It can be interpreted in terms of the probability of molecular arrangement in a material or in terms of the nature of spontaneous change in materials and systems [3].

In any isolated physical system the direction of spontaneous change is always from molecular order to disorder. A container of hot water, for example, undergoes spontaneous cooling as the energy of motion of its microscopic particles decreases. The molecular change is from a condition of higher order to a condition of lesser order — what mathematicians now describe as greater chaos. The same change is, conversely, from a condition of lesser probability of arrangement to a condition of greater probability of arrangement.

Entropy is a concept, not a physical property. It is a measure of the extent of disorder in a system or of the probability of the arrangement of parts of a system. Greater probability implies greater disorder and higher entropy. Lesser probability implies lesser disorder (more order) and less entropy. The entropy is usually denoted by the symbol S and was defined in 1865 by the German physicist Clausius,

$$dS = \frac{dQ}{T} \tag{1.28}$$

Equation (1.28) defines a small change of entropy of a system dS between equilibrium states as the change of heat energy dQ divided by its absolute temperature T. It is seen that entropy has the dimension heat energy/temperature with the unit of joules/Kelvin (J/K) in S.I. units. Because the natural tendency of change of physical systems is always towards greater disorder (more chaos), the second law of thermodynamics can be expressed in terms of entropy:

> *The entropy of an isolated system spontaneously increases or remains the same.*

For a heat–work system the entropy represents the amount of energy that cannot be transformed into mechanical work.

In mathematical terms the second law can be written as

$$dS \geq 0 \tag{1.29}$$

For a finite and measurable heat flow, the entropy can be obtained by integrating (1.28).

$$\int dS = \int \frac{dQ}{T} \tag{1.30}$$

Entropy increases for heat gain when dQ is positive, but decreases for heat loss when dQ is then negative.

Alternatively to (1.28), it is possible to define entropy in terms of the natural logarithm of the mathematical probability, but this aspect is not pursued here.

In the ideal heat engine of Fig. 1.6(a) the entropy flow is negative from the high temperature source $S_{\mathrm{H}} = Q_{\mathrm{H}}/T_{\mathrm{H}}$ and positive into the low temperature sink $S_{\mathrm{L}} = Q_{\mathrm{L}}/T_{\mathrm{L}}$. The change of entropy $\int dS$ is therefore

$$\begin{aligned} \int dS &= -S_{\mathrm{H}} + S_{\mathrm{L}} \\ &= \frac{Q_{\mathrm{L}}}{T_{\mathrm{L}}} - \frac{Q_{\mathrm{H}}}{T_{\mathrm{H}}} \end{aligned} \tag{1.31}$$

Since $dS \geq 0$, (1.31) can be rearranged as

$$\frac{Q_{\mathrm{L}}}{Q_{\mathrm{H}}} \geq \frac{T_{\mathrm{L}}}{T_{\mathrm{H}}} \tag{1.32}$$

Equation (1.32) can be combined with the laws of thermodynamics for an ideal system (1.23) to give the thermodynamic efficiency.

$$\boldsymbol{\eta} = \frac{W}{Q_{\mathrm{H}}} = 1 - \frac{Q_{\mathrm{L}}}{Q_{\mathrm{H}}} \leq \left[1 - \frac{T_{\mathrm{L}}}{T_{\mathrm{H}}}\right] \tag{1.33}$$

The maximum theoretical efficiency deduced by reasoning based on entropy from (1.33) is therefore that $\boldsymbol{\eta}_{\max} = 1 - T_{\mathrm{L}}/T_{\mathrm{H}}$, which is equal to the Carnot efficiency of (1.24).

1.8.2. *Entropy on a cosmic scale*

Since energy always flows in such a direction as to make the entropy (disorder) increase, different forms of cosmological energy can be arranged in increasing entropy order. There is no associated temperature for gravitational energy or for planetary rotation and orbital motion so that the entropy is zero. Chemical reactions have entropies of the order 1–10 inverse electron volts. The cosmic microwave background radiation is the ultimate heat energy sink with entropy 10^4 inverse electron volts — no further energy degradation or conversion is possible [1].

The structure of the universe is not inherently stable. It possesses a succession of quantitative features, such as the values of a number of physical constants, which effectively arrest the normal processes of energy degradation favoured by thermodynamics. For example, the main energy flow is associated with the gravitational contraction of very large masses which converts the energy released into heat, light and motion. Gravitational energy remains, after 15 billion years of cosmic evolution, as predominant in quality and quantity. This is in apparent contradiction to the fact that large masses are unstable against gravitational collapse. There is no agreed scientific explanation for many paradoxical questions with regard to the structure and physical operation of the universe.

1.9. Power

Power P is the time rate of doing work or of expending energy and therefore has the dimension of energy (or work) divided by time.

$$\begin{aligned} P &= \frac{dW}{dt} \quad \begin{array}{l}\text{for small increments of time}\\ P \text{ is called the instantaneous power}\end{array} \\ P &= \frac{W}{t} \quad \begin{array}{l}\text{for larger increments of time}\\ P \text{ is called the average power}\end{array} \end{aligned} \tag{1.34}$$

In S.I. units the unit of power is the joule per second (J/s), which is called the watt (W). For practical purposes it is often convenient to use the kilowatt (kW) or megawatt (MW). Power in watts is not concerned exclusively with electrical engineering. The power ratings in watts of various animals or manufactured devices are given on a logarithmic scale in Fig. 1.8 [2], which has to be read carefully. For example, the installed electricity generation capacities in the USA and UK are close together on the scale but differ in magnitude by a factor of ten!

In terms of human perception it may sometimes be helpful to use the old British power unit of horsepower (HP).

$$1 \text{ horsepower (HP)} \equiv 746 \text{ W} \tag{1.35}$$

Energy converters with a mechanical output, such as combustion engines, tend to be rated in horsepower and the relative power ratings can be judged from the size (and sometimes noise) of their engines. In Fig. 1.8 the automobile, for example, is shown as having a power rating of about 0.3×10^6 W, which is roughly 400 HP.

It is important to clearly distinguish between power and energy. In particular, it is essential to avoid a common lay practice of using the terms interchangeably.

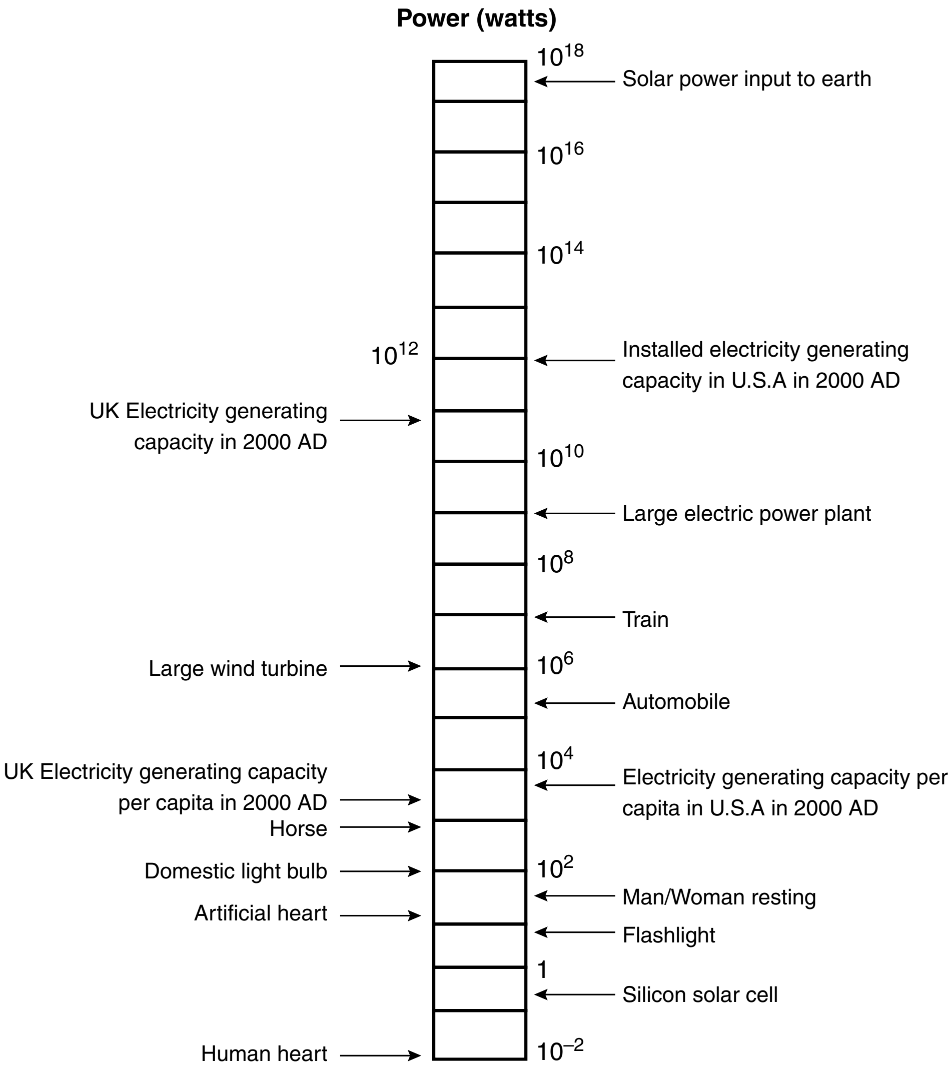


Fig. 1.8. Power ratings of various devices and animals (based on [2]).

Power is associated with time, whereas energy is independent of time.

$$\text{power} = \frac{\text{energy}}{\text{time}} = \frac{\text{work}}{\text{time}} \tag{1.36}$$

1.10. Units and Conversion Factors

The most common system of units used today in science and engineering applications is the International System of Units or Système International d'Unités (S.I.). Most physical sciences and engineering textbooks are now written in S.I. units, although older books still on library shelves may have written in foot-pound-second (fps) or centimetre-gramme-second (cgs) units.

Table 1.2 lists the basic physical properties of electrical and mechanical engineering systems together with their units and the symbols used in this text (which are common but not all universal). The common multiples and sub-multiples in S.I. units, with their names and symbols, are listed in Table 1.3.

Conversion factors between various basic S.I. units and their UK or US equivalents are given in Table 1.4 [4]. Many of these units are used in subsequent chapters of the book.

Table 1.2. The International System of Units (S.I.).

Property	Unit	Symbol
Basic		
Length	metre (UK), meter (US)	m
Mass	kilogramme	kg
Time	second	s
Temperature	kelvin	K
Electric current	ampere	A
Derived		
Velocity	metre per second	v (m/s)
Area	square metre	A (m^2)
Force	newton	F (kgm/s^2)
Energy (Work)	joule (newton-metre)	W (J *or* Nm)
Power	watt	P (J/s)

Table 1.3. Multiples and sub-multiples in S.I. units.

Unit	Symbol	Value
pico	p	10^{-12}
nano	n	10^{-9}
micro	μ	10^{-6}
milli	m	10^{-3}
centi	c	10^{-2}
kilo	k	10^{3}
mega	M	10^{6}
giga	G	10^{9}
tera	T	10^{12}

Table 1.4. Conversion factors [4].

Length	
1 millimetre (mm)	0.0393701 inch (in)
1 metre (m)	3.28084 feet (ft)
Area	
1 square centimetre (cm^2)	0.155000 in^2
1 square metre (m^2)	10.7639 ft^2
1 hectare = $10^4 m^2$	2.4710 acres
Volume	
1 cubic centimetre (cm^3)	0.0610237 in^3
1 cubic metre (m^3)	35.31477 ft^3
1 litre (1) (1000 cm^3)	1.75985 UK pints
1 imperial gallon (UK)	4.54596 litres
1 US gallon	3.78531 litres
1 barrel = 42 US gallons = 34.97 UK gallons = 159.00 litres	
Weight	
1 kilogramme (kg)	2.20462 lb
1 tonne (10^3 kg)	0.9984207 ton (UK)
1 ton (UK) or statute or long ton = 1.120 short tons	
Force	
1 newton (N)	0.2248 lb force
Pressure	
1 pascal (Pa)	1 N/m^2
1 bar = 10^5 Pa	14.50 lbf/in^2
1 lbf/in^2 (one pound per square inch or psi)	6.89476 kPa
Atmospheric pressure = 14.70 lbf in^{-2}	101.325 kPa
Velocity	
1 mile per hour (mph)	0.447 m/s
1 kilometre per hour (kph)	0.278 m/s

Table 1.5 lists some useful conversion data relating to heat energy and power and Table 1.6 represents conversion between different scales of temperature [4].

1.11. Problems on Energy and Power

Mechanical energy

1.1. A body of constant mass m is acted on by force F which results in linear motion at constant velocity v. Show that the linear momentum mv is equal to the time integral of the force.

Table 1.5. Conversion factors in power, heat and energy [4].

	Unit	Equivalents
Power		
	1 watt (W)	1 Joule/sec (J/s) = 0.001341 HP
	1 kilowatt (kW)	1000 W = 1.34 HP
	1 horsepower (HP)	745.7 W = 550 ft lb/sec
Power density		
	1 W/m^2	3.6 kJ/m^2/h = 0.317 BTU/ft^2/h
Heat energy		
	1 calorie (cal)	4.1868 J
	1 British thermal unit (BTU)	1055.06 J = 778.169 ft lb
	1 therm	10^5 BTU = 29.3 kWh = 1.05506×10^8 J
Heat energy density		
	1 kcal/m^2	0.3687 BTU/ft^2 = 1.163 Wh/m^2
	1 BTU/ft^3	3.726×10^4 J/m^2
	1 Langley	1 cal/cm^2 = 41868 J/m^2
Energy		
	1 Joule	1 watt-second (Ws)
	1 electron volt (eV)	1.602×10^{-19} J
	1 kilowatt hour (kWh)	3.6×10^6 J = 3.412×10^3 BTU

Table 1.6. Scales of temperature.

The centigrade (Celsius) scale of temperature has 100 degree units between the freezing point 0°C and boiling point 100°C of water at standard pressure.

The Fahrenheit scale has 180 degree units between the freezing point 32°F and boiling point 212°F of water. Therefore

$$100^\circ\text{C} \equiv 180^\circ\text{F}$$

and

$$^\circ\text{C} = 5/9\ (^\circ\text{F} - 32)$$

$$^\circ\text{F} = 9/5\ ^\circ\text{C} + 32$$

The Kelvin scale of temperature is measured from absolute zero −273.15°C, usually rounded to −273°C. Therefore, for temperatures greater than zero degrees centigrade,

$$\text{K} = {}^\circ\text{C} + 273$$

1.2. A body of mass 100 kg initially rests on a ledge 25 m above the ground. It then falls freely to the ground under the influence of gravity. Air friction may be neglected. Gravitational constant $g = 9.81\ \text{m/s}^2$.

(a) What are initial and final values of the potential energy?
(b) What are the initial value and final value after impact of the kinetic energy?
(c) Calculate the instantaneous velocity at the mid-height of the fall. Hint: Use energy balance.
(d) Calculate the values of potential energy and kinetic energy at the mid-height of the fall.

1.3. A force of 100 N acts on a mass of 100 kg.

(a) What is the resulting linear acceleration?
(b) If the steady-state velocity is 10 m/s, what are the values of the kinetic energy and momentum?

1.4. A mass of 1 kg is rotated in a horizontal circle, at the end of a rigid tie-rod, with an angular velocity of 10 rad/s. If the radius of gyration is 0.5 m, what is the instantaneous linear velocity of the mass? Calculate the torque and angular acceleration if a force of 10 N is needed to maintain the rotation.

1.5. Calculate the moment of inertia of the rotating mass in Qn. 1.4.

1.6. A mass of 1 kg rotates in a horizontal circle, at a radius 0.5 m about its fixed anchor point, with an angular velocity of 10 rad/s. What is the kinetic energy of the motion?

1.7. If a mass of 10 kg rotates around a circle of 1 m radius at 1800 rpm, what is its energy of motion?

Thermal energy

1.8. An imperial gallon of water is uniformly heated so that its temperature increases by 20°C. What is the rise of its heat energy content?

1.9. Two equal masses of water are mixed in a container. What is the final temperature of the mixture if (a) the two initial temperatures T_{in} are equal, (b) one mass has an initial temperature twice that of the other?

1.10. In the UK the original steam engines designed by Watt and Newcomen used reservoir temperatures of 100°C and 10°C. What was the maximum theoretical efficiency?

1.11. A heat engine operates with a high temperature source of 900 K and initial heat energy of 500 MJ. Its low temperature sink operates at 300 K. The maximum realisable efficiency is one-half the value of the theoretical maximum value.

(a) Calculate the maximum working value of the efficiency.
(b) What is the maximum work output?

1.12. For the purpose of converting heat energy into useful work from an ambient temperature of 100°C, is it better to have one heat source Q of temperature 400°C or two equal sources Q of temperature 200°C?

1.13. A heating boiler has a full-load working efficiency of 65%. It is used to heat a building from the outside temperature of 35°F to 68°F. What is the total thermal efficiency?

1.14. For the steam boiler–electricity generator system of Fig. 1.5

(a) Show that the first law of thermodynamics is satisfied.
(b) Calculate the efficiency of the turbine.
(c) What information is needed in order to calculate the energy discharged through the chimney?
(d) Calculate the efficiency of the generator.

1.15. A Carnot engine has a low temperature sink of 10°C and a maximum theoretical efficiency of 38%. By how much does the temperature of the high temperature source need to increase in order to raise the efficiency to 50%?

1.16. Explain what happens to the power input to a refrigerator if its door is left open in a warm room.

1.17. A high temperature fluid contains 1000 MJ of energy at 600°C. This fluid powers a mechanical converter of Carnot efficiency 30%.

(a) What is the temperature of the sink fluid?
(b) What is the change of entropy?

Units and unit conversions

1.18. What are the centigrade (Celsius) equivalents of the following temperatures in degrees Fahrenheit? (a) 212°F, (b) 100°F, (c) 32°F, (d) 0°F.

1.19. What are the Fahrenheit equivalents of the following temperatures in degrees centigrade? (a) 212°C, (b) 100°C, (c) 32°C, (d) 0°C.

1.20. At what value of temperature is the temperature reading in degrees centigrade equal to the reading in degrees Fahrenheit?

1.21. What is the centigrade equivalent of 75.8°F?

1.22. What is the Fahrenheit equivalent of 19.6°C?

1.23. A modern electric power station has a full load of 2000 MW. What are the equivalent values in (a) horsepower, (b) joules/second, (c) kilowatts, (d) footpounds/second?

1.24. A solar water heating panel has a thermal energy rating of 50 MJ. What is the rating in kilowatt hours?

1.25. The large wind turbine at Burger Hill, Orkney, Scotland, is rated at 3 MW. What is the equivalent rating in horsepower?

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CHAPTER 2

ENERGY RESOURCES AND ENERGY USE

2.1. Energy Input to the Earth

Figure 2.1 shows the accepted energy flow pattern for the earth [1]. All of the numerical values in this are obtained from scientifically measured data but are subject to measurement error and to slight intrinsic variations of value.

2.1.1. *Solar radiation rate and annual variation*

Solar radiation flows continuously through the earth's atmosphere onto its surface. Each square metre of surface area at the atmospheric boundary intercepts a normal (i.e. perpendicular) radiation, when facing the sun, of almost constant value. The orbit of the earth around the sun is not precisely circular but is slightly elliptical. For this reason the sun–earth distance is 91.4 million miles in January and 94.5 million miles in July. This small variation accounts for an annual difference of 3% to 4% in the solar radiation rate at the edge of the atmosphere. For calculation purposes it is convenient to assume a constant radiation rate and this is embodied in the "solar constant" which has a present value 1377 W/m^2.

If the earth is assumed to be perfectly spherical it has a diametric plane πr^2, where r is the mean earth radius. The solar radiation intercepted is therefore at a rate 1377 πr^2 watts, if radius r is in metres. A figure for the mean earth radius is 6.324 million metres, resulting in

$$\begin{aligned}\text{Earth radiation rate} &= 1377 \times \pi \times (6.324 \times 10^6)^2 \\ &= 1.73 \times 10^{17}\ \text{W} \\ &= 1.73 \times 10^{17}\ \text{J/s}\end{aligned}$$

In a year of 365.25 days the total input radiation energy is therefore

$$\begin{aligned}W_{\text{annual}} &= 365.25 \times 24 \times 3600 \times 1.73 \times 10^{17} \\ &= 5.46 \times 10^{24}\ \text{J}\end{aligned}$$

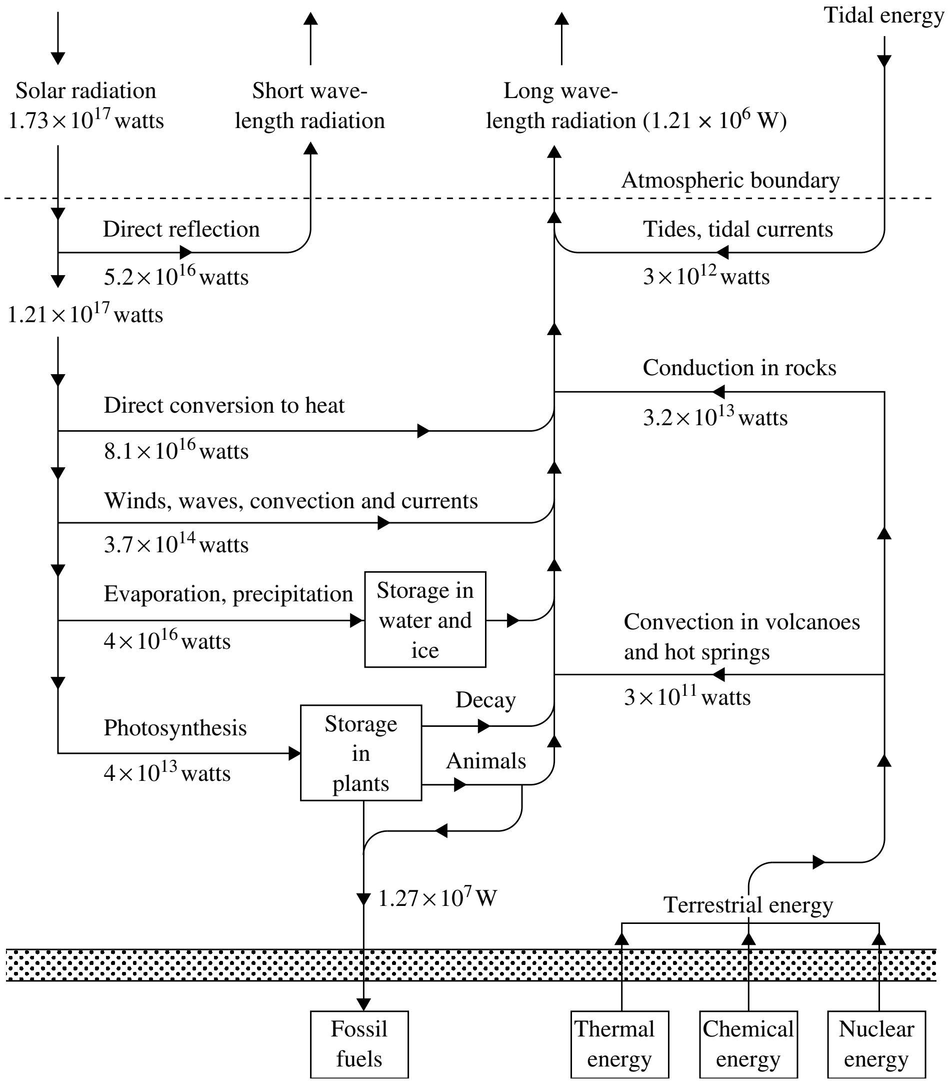

Solar radiation
1.73×10^{17} watts
Short wave-length radiation
Long wave-length radiation (1.21×10^6 W)
Tidal energy
Atmospheric boundary
Direct reflection
5.2×10^{16} watts
Tides, tidal currents
3×10^{12} watts
1.21×10^{17} watts
Conduction in rocks
3.2×10^{13} watts
Direct conversion to heat
8.1×10^{16} watts
Winds, waves, convection and currents
3.7×10^{14} watts
Evaporation, precipitation
4×10^{16} watts
Storage in water and ice
Convection in volcanoes and hot springs
3×10^{11} watts
Decay
Photosynthesis
4×10^{13} watts
Storage in plants
Animals
1.27×10^7 W
Terrestrial energy
Fossil fuels
Thermal energy
Chemical energy
Nuclear energy

Fig. 2.1. Rate of energy flow diagram for the earth [1].

The radiant input energy is staggeringly large. During the year 2000 the total primary energy consumption in the world was 8752.4 million tonnes of oil equivalent [2]. In terms of various energy units this is

$$\begin{aligned} W_{\text{World Consumption}} &= 8752.4 \text{ mtoes} \\ &= 8752.4 \times 12 \times 10^9 \text{ kWh} \\ &= 8752.4 \times 12 \times 10^9 \times 3.6 \times 10^6 \text{ J} \\ &= 3.781 \times 10^{20} \text{ J} \end{aligned}$$

The input solar radiation, for the year 2000, was about $(5.46 \times 10^{24})/(3.781 \times 10^{20})$, or 14,440 times the total world primary energy consumption.

2.1.2. *Terrestrial energy from inside the earth*

Energy flows outwardly from the interior of the earth to its surface at an estimated rate 0.063 W/m^2, being a resultant of thermal, chemical and nuclear sources, Fig. 2.1. If the earth is assumed to be a perfect sphere, the outward flow of power is then $0.063 \times 4\pi r^2$ watts, where r is the earth's radius in metres. The total heat flow rate is about 3.2×10^{13} W from rocks plus 3×10^{11} W due to convection by hot springs and volcanoes. It is thus seen that about 99% of the outward-flowing terrestrial energy is due to conduction in rocks. This is discussed further in Chapter 7.

2.1.3. *Tidal (gravitational) input energy*

Gravitational energy derived from the locations and motions of the sun, earth and moon is responsible for the ocean tides and currents. The use of this energy is discussed in Chapter 9. Tidal energy is estimated to represent an energy input at the rate 3×10^{12} W, or about one-tenth of the energy flow rate outward from the earth's interior.

Comparison of the three sources of input energy in Fig. 2.1 shows that the solar input is about 5000 times the sum of the other sources. It is clear that the earth does not suffer from an energy shortage. There is natural energy in abundance. But serious technical problems arise with regard to the distribution, location, collection, conversion and storage of energy in its various forms. Even more serious are the human issues concerning the ownership and stewardship of the resources.

2.2. Energy Flow upon the Earth from Natural Sources

About 47% of the incoming solar radiation, i.e. 8.1×10^{16} W, is absorbed by the oceans, landmass and atmosphere. This is converted directly to heat energy at the ambient surface temperature.

The earth's hydrological cycle consists of evaporation, precipitation and surface run-off of water. As water vaporises, it absorbs heat — sometimes referred to as the latent heat of evaporation — and rises into the air and atmosphere. On precipitation most of this heat is released, together with the potential energy of its location and the kinetic energy of its pre-impact motion, as low temperature heat. Some portion of this hydrological component of energy is stored in rivers and lakes or in masses of ice. About 23% (4×10^{16} W) of the solar input radiation is routed via the hydrological cycle.

A small fraction, about 0.21% (3.7×10^{14} W), of the input radiation drives the ocean and atmospheric convections and circulations. This energy appears in the form of wind, wave and ocean current motions, which are all dissipated as low temperature heat due to friction.

The photosynthesis of plants is the process whereby some of the energy of solar radiation is captured by the chlorophyll of plant leaves. This is discussed in detail in Chapter 13. Solar energy combines with carbon dioxide (CO_2) and water (H_2O) to produce chemical carbohydrates plus oxygen. The stored energy in the leaves and plants is dissipated when the vegetation is consumed or decays, Fig. 2.1. Only the small proportion 4×10^{13} W or 0.0023% of the solar input power is involved in photosynthesis. Nevertheless, the annual energy of photosynthesis is of the same order of magnitude (10^{20} J) as the present world commercial energy consumption. It is the process of plant decay that is largely the source of the fossil fuel deposits [1, 2].

2.3. Energy Outflow from the Earth

About 30% of the incoming solar radiation is immediately reflected back into space in the form of short-wave radiation, at a rate of 5.2×10^{16} W. But the earth has to maintain an energy balance in order to avoid cumulative rises or falls of overall temperature. For energy balance the total input energy must equal the sum of the component directly re-radiated plus the sum of the components stored or converted to other forms.

For example, the 47% (8.1×10^{16} W) of the incident radiation converted to low-grade heat, Fig. 2.1, is then re-radiated as long-wavelength radiation. Also re-radiated is most of the input energy from the other solar input routes plus the tidal and terrestrial input components. It can be seen in Fig. 2.1 that the input solar radiation is equal to the sum of the two outgoing radiation components — the amount of energy stored being of a much lower order of magnitude.

2.4. Energy Stored Within the Fossil Fuels

The burial of vegetation under successive layers of sedimentary sands and rocks has been going on for an estimated 600 million years. Each major climatic or geological change causes further changes in the earth's crust. Physical compressions and chemical decomposition have, during the course of time, resulted in deposits of the so-called fossil fuels — coal, oil-shale, petroleum and natural gas. These constitute sites of extremely concentrated, stored solar energy. The time-scale of the laying down of the fossil fuel deposits is such that, in terms of the human lifespan, they can be considered non-renewable. Once they are extracted and used they are gone forever.

The main change of human lifestyle and conduct in Western countries over the past 300 years has been to convert from agriculture-based societies and economies to industry-based societies and economies. Many of the key events and features of this profound historical change, known as the Industrial Revolution, started in Britain, which was a dominant world power during the 18th and 19th centuries. The Industrial Revolution was initially fuelled by coal and now continues to be fuelled by coal, oil and natural gas. These fuels, together with nuclear and natural-flow hydro, are often called primary fuels. They are usually converted to other forms of energy. Great inroads have been made into these initially vast stores of concentrated energy so that they are now significantly depleted. Given that the world demand for energy still continues to rise, it is important to assess the remaining reserve stocks of the fossil fuels. Present rates of fuel consumption can be measured accurately but future demand has to be estimated and is therefore subject to uncertainties. Further uncertainty arises with regard to the possible discovery of new and accessible sources of fossil fuels. It is certain that the passage of time reduces both the number of undiscovered fuel deposits and the reserves available.

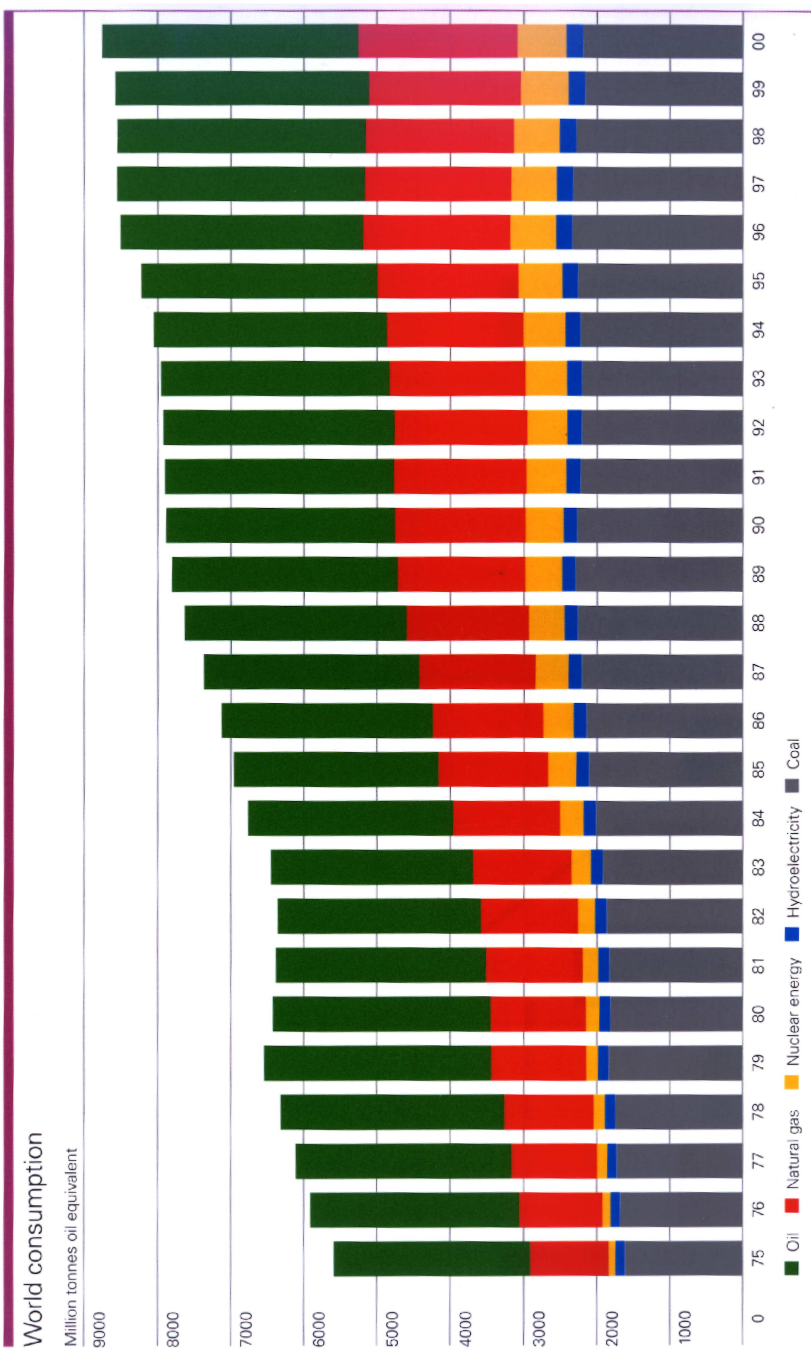
Estimates of the rates of use and the years of fossil-fuel reserves remaining are given in Figs. 2.2, 2.3 [3]. Some sources of information quote the reserves data in terms of the reserve/production (R/P) ratio. If the R/P ratio increases, this implies that the new discoveries (or revised reserve estimates) have exceeded the energy consumption within the particular time period. Figure 2.2 includes information concerning oil supplies, which is the most critical from the viewpoint of years of reserves. Although the R/P ratio for oil has been steadily growing since the mid-1970s, the critical feature is that the stock of natural crude oil reserves remaining is just over 40 years for the world. Most of the accessible oil reserves remain in the Middle East, which continues to be the main provider of oil for the rest of the world. This is discussed in detail in Chapter 5.

Numerical information for the remaining world stock of natural gas is shown in Fig. 2.3. As in the case of oil, the R/P value is slowly increasing but the remaining world reserve stock is estimated at between 60 and 70 years. It would be foolish to assume that the R/P values for oil and for gas will continue to rise so as to always maintain two or three human generations of reserves.

The situation with regard to coal reserves is less serious because the estimated stock will outlast both the oil and the gas by almost 200 years. Moreover the distribution of the coal reserves is geographically very widespread, such that it is likely to remain available all over the world, as is discussed in Chapter 4.

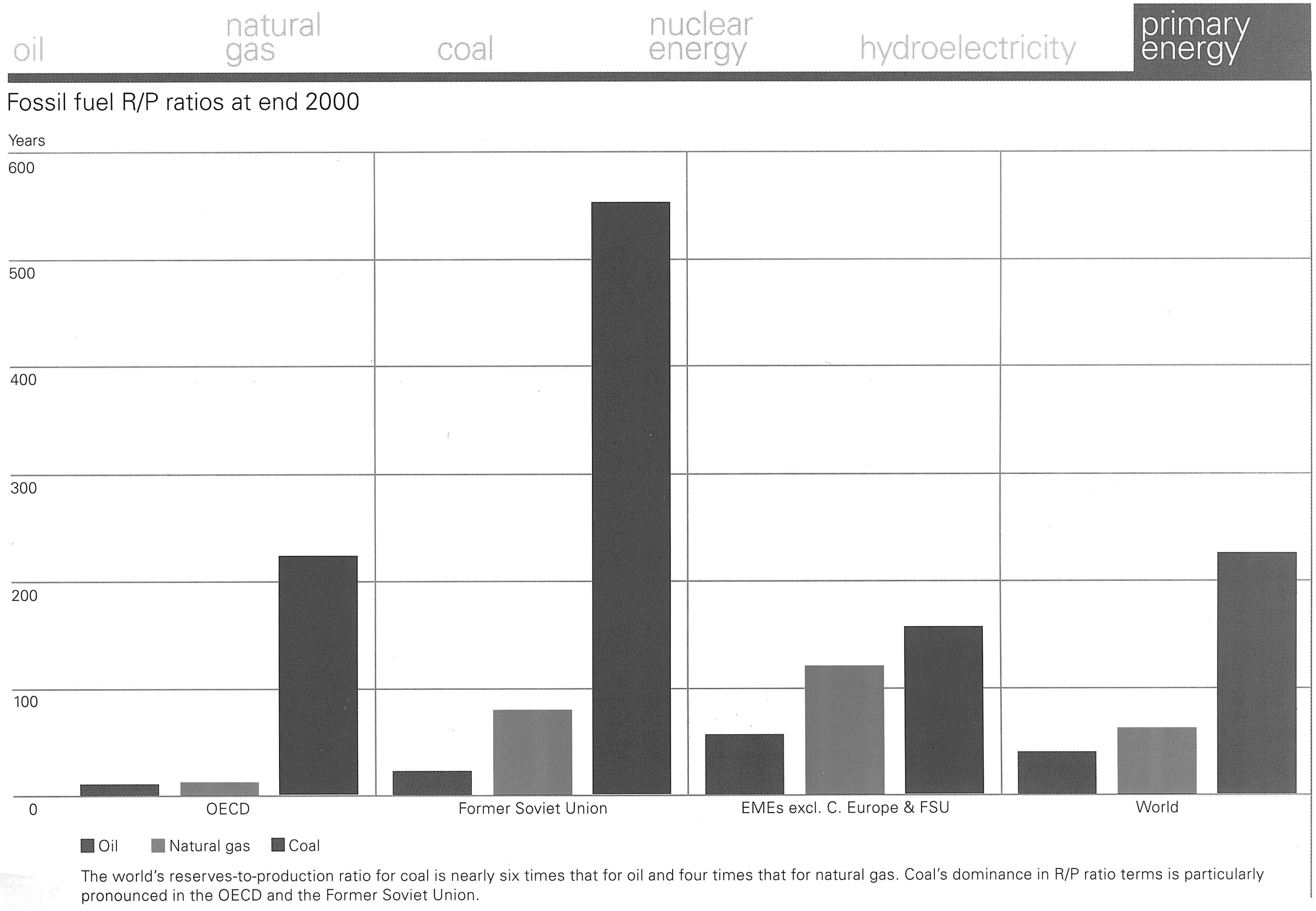
Figure 2.3 summarises the year 2000 world fossil fuel reserve situation, divided between three groupings. The OECD group (see Table 2.1), which includes the UK (Great Britain) and the USA, is well off for coal, mainly due to vast deposits in the USA. For both oil and natural gas, however, the long-term situation for OECD is bleak. Britain is exceptional in the group in having an oil- and natural-gas-based economy. What will happen to the British economy when (not if) the oil runs out?

The data of Figs. 2.2, 2.3 has the most profound implications. Will the large reserve stocks of oil and gas in the Middle East continue to be available for purchase to the rest of the world? Will there be future major dislocations of the world



Total primary energy consumption increased by over 2% in 2000, well above the sub-1% pace of the previous three years. Natural gas was once again the fastest-growing fuel, followed by nuclear energy.

Fig. 2.2. World consumption of prime fuels, 1975–2000 [3].

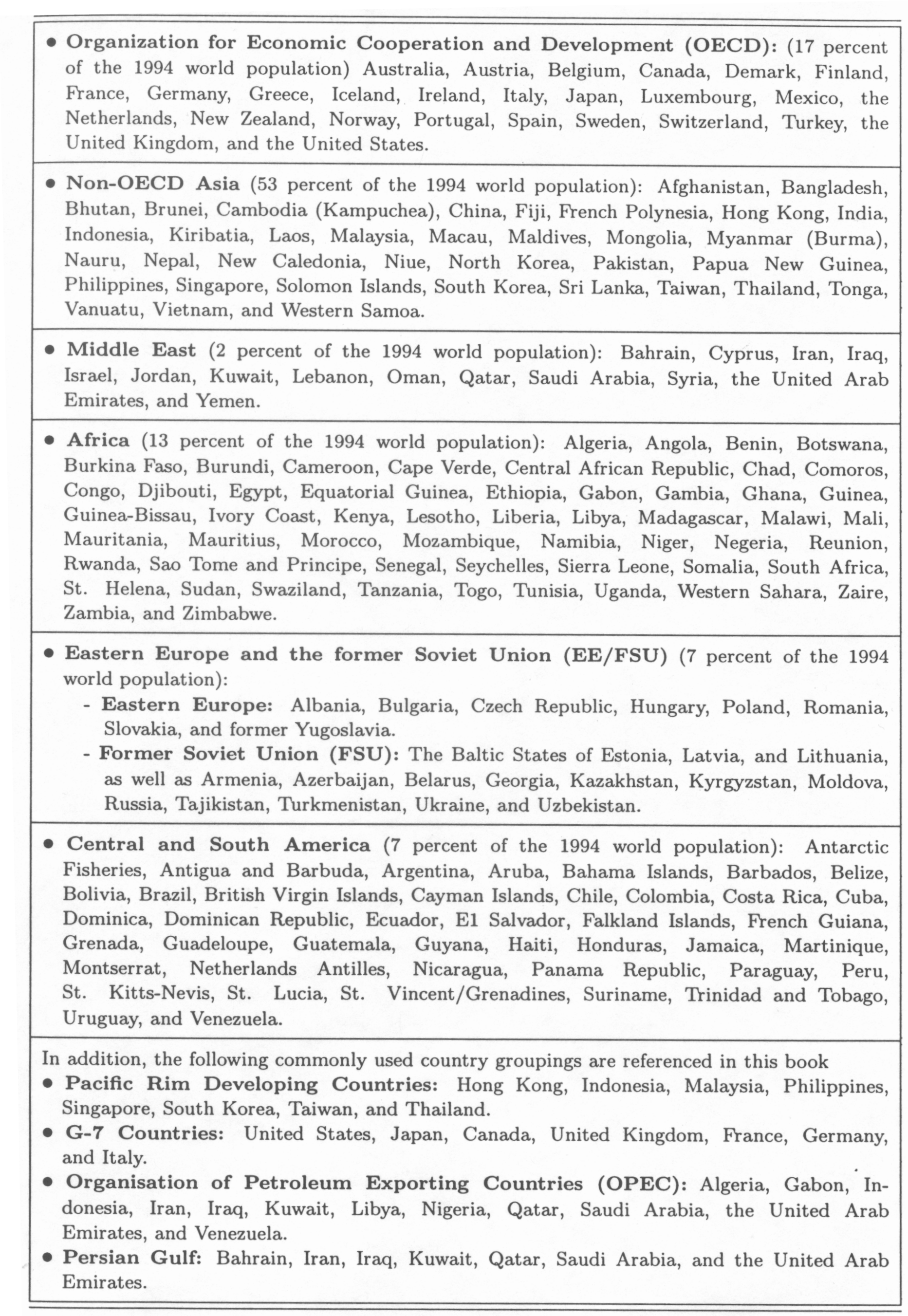


Fossil fuel R/P ratios at end 2000

The world's reserves-to-production ratio for coal is nearly six times that for oil and four times that for natural gas. Coal's dominance in R/P ratio terms is particularly pronounced in the OECD and the Former Soviet Union.

Fig. 2.3. World fossil fuel R/P ratios at the end of 2000 [3].

Table 2.1. Country groupings in the "Energy" map, Fig. 2.4 [4].



- **Organization for Economic Cooperation and Development (OECD):** (17 percent of the 1994 world population) Australia, Austria, Belgium, Canada, Demark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom, and the United States.
- **Non-OECD Asia** (53 percent of the 1994 world population): Afghanistan, Bangladesh, Bhutan, Brunei, Cambodia (Kampuchea), China, Fiji, French Polynesia, Hong Kong, India, Indonesia, Kiribatia, Laos, Malaysia, Macau, Maldives, Mongolia, Myanmar (Burma), Nauru, Nepal, New Caledonia, Niue, North Korea, Pakistan, Papua New Guinea, Philippines, Singapore, Solomon Islands, South Korea, Sri Lanka, Taiwan, Thailand, Tonga, Vanuatu, Vietnam, and Western Samoa.
- **Middle East** (2 percent of the 1994 world population): Bahrain, Cyprus, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, the United Arab Emirates, and Yemen.
- **Africa** (13 percent of the 1994 world population): Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Djibouti, Egypt, Equatorial Guinea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Ivory Coast, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Negeria, Reunion, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, St. Helena, Sudan, Swaziland, Tanzania, Togo, Tunisia, Uganda, Western Sahara, Zaire, Zambia, and Zimbabwe.
- **Eastern Europe and the former Soviet Union (EE/FSU)** (7 percent of the 1994 world population):
  - **Eastern Europe:** Albania, Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovakia, and former Yugoslavia.
  - **Former Soviet Union (FSU):** The Baltic States of Estonia, Latvia, and Lithuania, as well as Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, and Uzbekistan.
- **Central and South America** (7 percent of the 1994 world population): Antarctic Fisheries, Antigua and Barbuda, Argentina, Aruba, Bahama Islands, Barbados, Belize, Bolivia, Brazil, British Virgin Islands, Cayman Islands, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, E1 Salvador, Falkland Islands, French Guiana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Montserrat, Netherlands Antilles, Nicaragua, Panama Republic, Paraguay, Peru, St. Kitts-Nevis, St. Lucia, St. Vincent/Grenadines, Suriname, Trinidad and Tobago, Uruguay, and Venezuela.

In addition, the following commonly used country groupings are referenced in this book

- **Pacific Rim Developing Countries:** Hong Kong, Indonesia, Malaysia, Philippines, Singapore, South Korea, Taiwan, and Thailand.
- **G-7 Countries:** United States, Japan, Canada, United Kingdom, France, Germany, and Italy.
- **Organisation of Petroleum Exporting Countries (OPEC):** Algeria, Gabon, Indonesia, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, the United Arab Emirates, and Venezuela.
- **Persian Gulf:** Bahrain, Iran, Iraq, Kuwait, Qatar, Saudi Arabia, and the United Arab Emirates.

Note: The G7 group of countries became the G8 group in 1999, when Russia became a member.

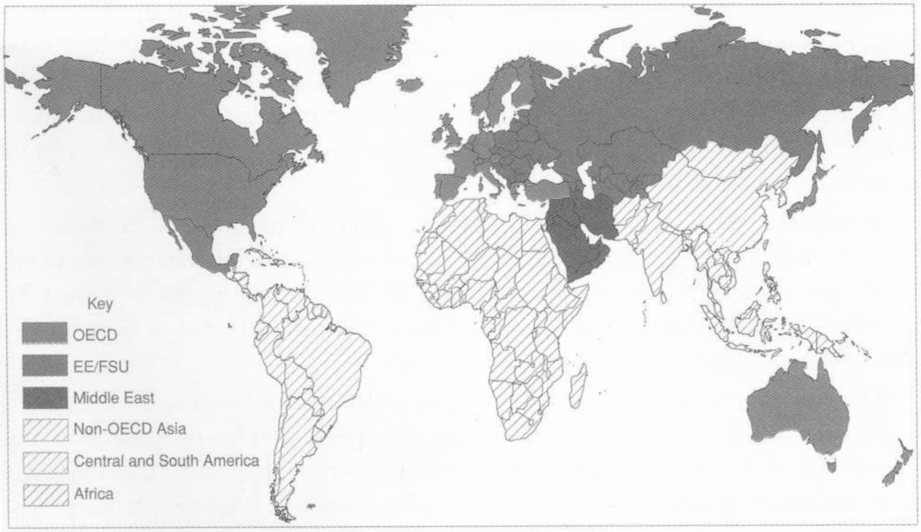
economy similar to that of 1973 when the price of oil quadrupled within a year? Will the need for oil create political, perhaps military, crises between nations or groups of nations?

2.5. Energy Production and Consumption

2.5.1. *Energy consumption in the world*

For the purpose of energy production and consumption, the countries of the world can be divided into the six groupings shown in Fig. 2.4. Member countries of the various groups are listed in Table 2.1 [4]. Details of the past production and consumption of separate energy forms, country by country, are given and discussed in later sections of the book.

The world situation, as at the end of 2000, is shown in Fig. 2.2. Energy consumption, in almost all its forms, continues to increase. From 1970 to 2000 the primary energy consumption increased from 4900 to 8752 million tonnes of oil equivalent (mtoe), which represents an increase of 78.6% over the original value. There is no evidence that this trend will reverse, although the rate of increase has slowed down since 1996. If figures are taken for the 11-year period 1990–2000, the world consumption of primary energy increased by an average of (8752.4–7885.7)/11, which is 78.8 mtoe/year.



Source: US Energy Information Administration, Office of Integrated Analysis and Forecasting.

Fig. 2.4. Map of six basic country energy groupings [4].

Table 2.2. World energy consumption (mtoes) [3].

oil natural gas coal nuclear energy hydroelectricity **primary energy**

Consumption*

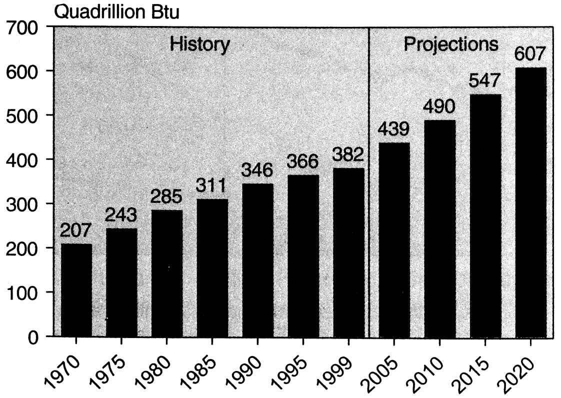
Million tonnes oil equivalent	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	**2000**	Change 2000 over 1999	2000 share of total
USA	1932.2	1929.3	1961.9	2002.1	2044.8	2080.6	2146.3	2158.3	2170.1	2222.0	**2278.6**	2.5%	26.0%
Canada	202.1	205.4	209.2	214.2	222.9	219.4	225.6	227.7	221.9	224.6	**231.8**	3.2%	2.6%
Mexico	99.0	101.7	102.8	103.8	111.6	107.5	112.2	116.6	122.5	122.8	**127.4**	3.8%	1.5%
Total North America	2233.3	2236.4	2273.9	2320.1	2379.3	2407.5	2484.1	2502.6	2514.5	2569.4	**2637.8**	2.7%	30.1%
Argentina	41.0	43.4	44.0	45.6	47.0	48.8	50.9	52.2	54.5	55.6	**54.1**	−2.6%	0.6%
Brazil	89.7	91.8	95.2	97.4	100.9	106.7	113.8	121.5	126.0	127.5	**132.7**	4.1%	1.5%
Chile	11.3	11.3	12.1	12.7	14.0	15.1	16.8	19.7	19.4	20.7	**22.1**	6.7%	0.3%
Colombia	19.1	19.4	19.9	20.7	21.2	21.9	22.7	23.5	23.0	20.3	**20.6**	1.8%	0.2%
Ecuador	4.7	5.3	5.1	5.4	5.9	5.6	6.3	7.2	7.3	6.7	**7.2**	7.5%	0.1%
Peru	7.1	6.9	7.0	7.5	8.1	8.9	9.1	9.1	9.4	9.5	**9.2**	−3.4%	0.1%
Venezuela	41.5	42.4	43.5	44.6	46.4	49.4	50.6	53.3	55.9	51.5	**52.9**	2.7%	0.6%
Other S. & Cent. America	55.2	55.7	57.2	59.2	62.1	64.1	66.5	68.3	70.4	71.6	**72.8**	1.6%	0.8%
Total S. & Cent. America	269.6	276.2	284.0	293.1	305.6	320.5	336.7	354.8	365.9	363.4	**371.6**	2.3%	4.2%
Austria	22.3	23.5	22.7	22.8	22.7	23.1	24.1	25.1	25.7	26.1	**25.4**	−2.7%	0.3%
Belgium & Luxembourg	55.8	57.5	57.7	55.9	55.7	57.7	60.2	61.5	64.1	65.4	**66.7**	2.0%	0.8%
Bulgaria	27.0	21.6	20.4	21.9	21.1	22.5	23.5	20.8	20.6	18.6	**19.5**	5.3%	0.2%
Czech Republic	50.2	46.1	40.7	39.3	38.3	38.8	41.1	40.2	39.0	36.7	**38.6**	5.2%	0.4%
Denmark	16.8	19.5	17.9	19.2	20.7	20.2	24.1	21.7	20.6	19.9	**18.8**	−5.4%	0.2%
Finland	22.3	22.6	21.8	21.8	23.2	21.9	23.4	24.1	24.2	24.6	**24.9**	1.2%	0.3%
France	220.9	233.0	234.2	235.7	229.6	237.0	247.4	244.1	250.2	253.0	**258.2**	2.1%	2.9%
Germany	351.8	342.7	338.2	335.4	332.8	334.6	346.0	340.3	336.6	330.6	**329.4**	−0.4%	3.8%
Greece	24.0	23.9	24.8	24.9	25.5	26.2	26.4	26.6	28.1	29.1	**29.8**	2.4%	0.3%
Hungary	27.1	26.0	23.7	23.3	23.8	24.0	24.7	24.2	24.2	24.1	**23.4**	−2.8%	0.3%
Iceland	1.1	1.0	1.1	1.2	1.2	1.2	1.3	1.4	1.4	1.5	**1.6**	5.6%	†
Republic of Ireland	8.5	9.0	9.0	9.3	9.8	10.1	10.7	11.5	12.2	13.1	**13.5**	3.7%	0.2%
Italy	149.8	151.6	151.9	148.6	148.1	156.5	155.8	157.4	161.9	165.9	**166.0**	0.1%	1.9%
Netherlands	76.4	79.2	78.2	79.8	79.6	82.8	85.3	84.8	84.6	82.7	**85.1**	2.9%	1.0%
Norway	22.0	20.8	21.8	22.7	22.6	23.5	22.5	23.8	24.1	24.4	**25.8**	5.6%	0.3%
Poland	105.3	100.8	94.7	96.5	95.7	95.9	100.2	98.1	93.5	90.5	**88.0**	−2.7%	1.0%
Portugal	14.7	15.3	16.3	16.1	16.4	17.8	17.3	18.5	20.5	22.2	**25.5**	15.0%	0.3%
Romania	59.0	48.7	46.8	45.5	43.5	46.2	46.0	42.9	38.8	34.5	**34.5**	−0.1%	0.4%
Slovakia	20.5	18.7	18.1	16.9	16.4	16.9	17.2	16.9	16.8	17.4	**17.2**	−0.8%	0.2%
Spain	89.0	90.5	94.0	92.0	94.7	98.8	100.8	108.2	114.5	120.2	**125.9**	4.7%	1.4%
Sweden	43.1	43.8	42.1	41.3	43.8	42.8	43.9	42.9	43.5	43.9	**39.6**	−9.8%	0.5%
Switzerland	23.5	23.9	24.2	23.7	24.6	23.7	23.8	24.8	25.1	25.1	**24.8**	−1.1%	0.3%
Turkey	49.5	50.1	54.8	58.6	57.5	60.8	68.0	70.7	71.8	71.0	**74.1**	4.3%	0.8%
United Kingdom	212.6	217.2	215.9	218.6	215.5	216.3	227.5	222.4	225.7	223.4	**226.1**	1.2%	2.6%
Other Europe	48.2	44.1	38.2	36.0	31.7	33.1	36.4	38.0	39.2	35.0	**35.4**	1.2%	0.4%
Total Europe	1741.4	1731.1	1709.2	1707.0	1694.5	1732.4	1797.6	1790.9	1806.9	1798.9	**1817.8**	1.1%	20.8%
Azerbaijan	22.9	22.0	18.8	16.2	15.6	15.9	12.4	11.2	10.7	11.5	**12.4**	8.1%	0.1%
Belarus	38.4	38.1	37.1	28.6	25.3	23.6	21.4	23.5	21.8	20.0	**20.1**	0.7%	0.2%
Kazakhstan	73.6	72.5	73.1	64.6	56.9	50.0	44.8	39.8	38.2	33.6	**37.2**	10.9%	0.4%
Lithuania	17.5	18.1	11.5	8.6	7.5	8.5	9.3	8.9	9.5	8.0	**7.7**	−3.7%	0.1%
Russian Federation	853.3	842.4	800.4	749.6	681.3	646.4	629.1	595.6	595.2	606.8	**621.3**	2.4%	7.1%
Turkmenistan	13.7	14.0	13.5	11.6	12.9	11.1	12.0	12.1	13.5	14.7	**16.1**	10.1%	0.2%
Ukraine	273.4	249.3	219.5	185.1	158.1	148.6	142.9	140.0	133.8	135.0	**131.7**	−2.4%	1.5%
Uzbekistan	50.5	48.9	46.1	47.2	46.8	46.7	48.1	50.0	51.6	53.8	**53.8**	†	0.6%
Other Former Soviet Union	54.8	43.7	33.0	25.4	20.1	18.7	17.2	18.8	18.3	16.4	**17.2**	4.5%	0.2%
Total Former Soviet Union	1398.1	1349.0	1253.0	1136.9	1024.5	969.5	937.2	899.9	892.6	899.8	**917.5**	2.0%	10.4%
Iran	69.1	71.2	74.4	76.9	84.0	92.0	98.5	102.9	104.8	109.3	**115.0**	5.2%	1.3%
Kuwait	11.1	4.1	7.5	9.8	11.4	14.2	15.7	16.4	16.8	16.4	**16.7**	1.9%	0.2%
Qatar	6.7	7.7	12.2	13.0	13.0	13.1	13.4	14.3	14.5	15.4	**14.2**	−8.2%	0.2%
Saudi Arabia	81.3	87.0	85.8	88.1	92.0	90.1	93.7	96.6	100.9	102.5	**104.7**	2.1%	1.2%
United Arab Emirates	27.9	34.9	33.8	34.9	37.7	40.3	42.3	42.4	39.2	41.3	**44.3**	7.2%	0.5%
Other Middle East	60.3	57.2	63.5	65.8	68.5	74.4	78.8	84.5	87.6	90.1	**92.3**	2.4%	1.1%
Total Middle East	256.4	262.1	277.2	288.5	306.6	324.1	342.4	357.1	363.8	375.0	**387.2**	3.2%	4.5%
Algeria	24.2	25.1	25.7	26.4	26.8	27.8	27.8	26.5	27.5	28.4	**30.7**	8.2%	0.4%
Egypt	31.6	31.9	31.9	32.2	32.8	34.8	36.7	38.3	40.0	42.7	**44.3**	3.9%	0.5%
South Africa	90.5	89.6	87.2	89.9	95.2	100.7	105.9	109.1	108.7	107.7	**108.3**	0.5%	1.2%
Other Africa	65.9	66.1	68.8	71.1	73.2	75.0	77.1	78.8	81.2	83.9	**86.1**	2.7%	1.0%
Total Africa	212.2	212.7	213.6	219.6	228.0	238.3	247.5	252.7	257.4	262.7	**269.4**	2.6%	3.1%
Australia	89.0	84.9	86.4	86.2	91.6	95.3	99.1	101.4	102.6	102.8	**106.0**	3.1%	1.2%
Bangladesh	6.5	6.6	7.1	7.7	8.2	9.6	9.9	10.5	10.2	10.8	**12.8**	18.1%	0.1%
China	668.0	677.0	703.7	738.2	788.8	831.6	887.0	872.1	845.4	759.7	**752.7**	−0.9%	8.6%
China Hong Kong SAR	11.8	12.2	14.4	15.6	14.1	15.1	15.0	15.1	15.4	15.6	**15.5**	−0.9%	0.2%
India	182.7	193.7	205.4	210.9	222.8	239.3	257.7	268.5	275.0	281.5	**294.2**	4.5%	3.4%
Indonesia	52.3	56.3	60.2	63.8	66.9	72.0	79.1	83.2	78.9	82.9	**88.4**	6.6%	1.0%
Japan	428.3	443.2	449.7	454.9	477.2	490.6	500.8	504.5	497.9	505.9	**511.3**	1.1%	5.8%
Malaysia	21.5	23.6	25.2	28.9	31.4	32.3	35.3	36.7	36.1	39.0	**41.7**	6.9%	0.5%
New Zealand	12.0	12.1	12.7	12.7	12.9	13.1	13.5	13.9	13.4	14.1	**14.4**	2.3%	0.2%
Pakistan	24.4	25.1	26.7	28.7	30.7	33.2	34.8	34.9	36.2	37.7	**40.4**	7.0%	0.5%
Philippines	13.0	12.8	15.2	15.8	16.7	18.8	20.2	21.7	22.2	21.6	**21.7**	0.7%	0.2%
Singapore	20.3	20.6	22.7	24.4	28.1	29.3	28.9	30.4	30.6	29.6	**30.4**	2.8%	0.3%
South Korea	91.1	102.9	115.5	126.4	136.8	149.9	165.4	180.2	166.5	181.9	**192.3**	5.7%	2.2%
Taiwan	48.9	52.0	55.0	58.0	62.2	65.6	68.8	72.7	77.2	81.1	**85.5**	5.5%	1.0%
Thailand	28.8	32.6	35.5	40.1	44.8	51.4	57.4	60.2	57.4	59.2	**61.8**	4.5%	0.7%
Other Asia Pacific	76.1	77.3	78.7	81.5	82.0	83.5	85.4	83.9	82.3	79.6	**82.0**	3.0%	1.0%
Total Asia Pacific	1774.7	1832.9	1914.1	1993.8	2115.2	2230.6	2358.3	2389.9	2347.3	2303.0	**2351.1**	2.1%	26.9%
TOTAL WORLD	**7885.7**	**7900.4**	**7925.0**	**7959.0**	**8053.7**	**8222.9**	**8503.8**	**8547.9**	**8548.4**	**8572.2**	**8752.4**	**2.1%**	**100.0%**
of which: OECD	4440.4	4477.5	4523.9	4587.0	4679.6	4770.1	4937.4	4974.9	4986.4	5067.5	**5173.0**	2.1%	59.1%
European Union 15	1308.0	1329.3	1324.7	1321.4	1318.1	1345.8	1392.9	1389.1	1412.4	1420.1	**1434.9**	1.1%	16.4%
Other EMEs‡	1892.5	1940.8	2024.6	2114.8	2236.9	2364.6	2506.1	2554.5	2554.0	2499.4	**2555.3**	2.2%	29.2%

*In this Review, primary energy comprises commercially traded fuels only. Excluded, therefore, are fuels such as wood, peat and animal waste which, though important in many countries, are unreliably documented in terms of consumption statistics.

†Less than 0.05.

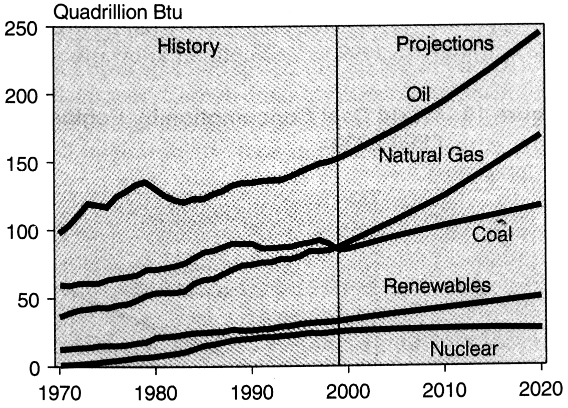
‡Excludes Central Europe and Former Soviet Union.

Some country-by-country details of primary energy consumption in the period 1990–2000 are given in Table 2.2 [3]. It can be seen that in 2000 the USA was, by far, the largest consumer, followed by China, the Russian Federation and Japan. The countries of North America and Western Europe consume just about one-half of the total world primary energy.



Sources: **History:** Energy Information Administration (EIA), Office of Energy Markets and End Use, International Statistics Database and *International Energy Annual 1999*, DOE/EIA-0219(99) (Washington, DC, January 2001). **Projections:** EIA, World Energy Projection System (2001).

Fig. 2.5. World energy consumption, 1970–2020 [5].



Sources: **History:** Energy Information Administration (EIA), Office of Energy Markets and End Use, International Statistics Database and *International Energy Annual 1999*, DOE/EIA-0219(99) (Washington, DC, January 2001). **Projections:** EIA, World Energy Projection System (2001).

Fig. 2.6. World energy consumption by fuel type, 1970–2020 [5].

Various predictions have been made about future world energy consumption. The figures differ slightly according to the assumed rates of growth but all surveys indicate continued increase. Figure 2.5, quoted from reference [5], uses the energy unit quadrillions of British thermal units (1 mtoe = 0.04×10^{15} BTU = 0.04 quadrillion BTU). Conversion factors between fuel values are subject to slight inconsistencies due to variations of fuel quality but the data of Fig. 2.5 agree with the values of Fig. 2.2.

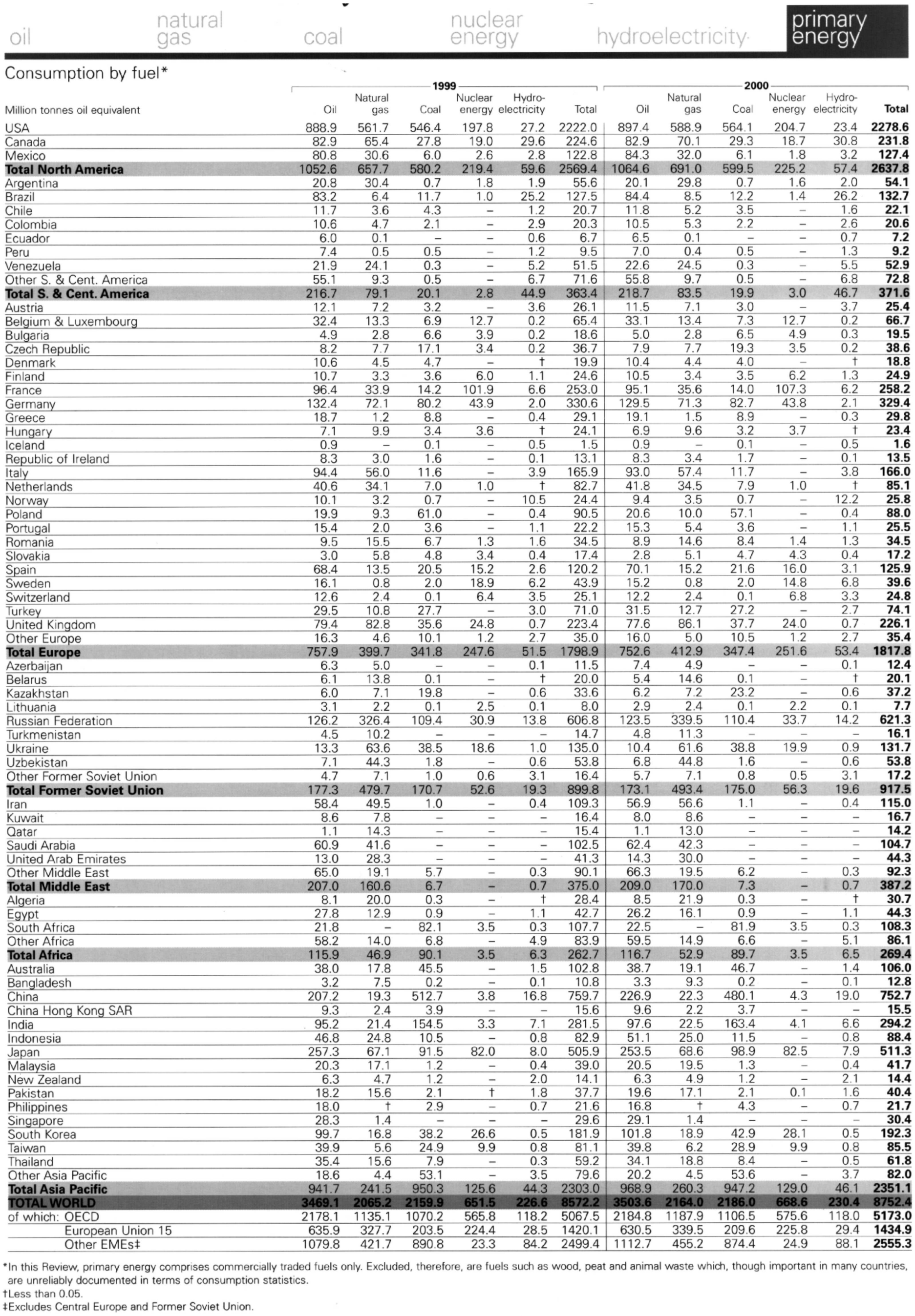
Recent consumption figures and future projections for different primary fuels are given in Fig. 2.6 and Table 2.3 [3]. The primary fuel most used is oil, which is needed in all regions. It is clear that oil and natural gas account for about 60% of present world demand. This makes even more urgent the need to address the remaining reserves situation indicated in Figs. 2.2 and 2.3. Country-by-country details of remaining individual fossil-fuel stocks of coal, oil and natural gas are given as appropriate tables in Chapters 4, 5 and 6, respectively.

World energy consumption in different nations occurs in patterns and is not only unequal but inequitable. Rather than consider only the energy consumption figures, it is instructive to consider the energy consumption per capita (i.e. per person of the population). Figure 2.7 shows the situation over the last 25 years with regard to different regions of the world. The North Americans consume twice as much energy per person as the Western Europeans, who, in turn, consume energy at about twice the average value for the world.

The use of energy is related directly to industrial productivity and to the Gross National Product (GNP) of a country, which is a rough measure of affluence. Other factors, such as the climate and the industry/agriculture ratio, are relevant but the GNP is a useful indicator of national prosperity. In per capita terms, the energy consumption is shown versus GNP in Fig. 2.8. Some corresponding data, with their sources, are given in Table 2.4. Figure 2.8 demonstrates that the calculated coordinate for the USA lies near a straight line extrapolated through the origin and the average intersection point. Above this diagonal line are represented the locations of prosperous countries having high GNP/capita. To the left of the diagonal line are grouped the countries of the European Economic Community (EEC) which achieve a high per capita GNP with about one-half the per capita energy consumption of the North Americans. The former Soviet Union and its former Eastern European satellites expend a lot of per capita energy to achieve relatively poor economic performance. Information about GNP/capita is not available for most of the OPEC oil producer countries.

The information in Fig. 2.8 should not be used to invoke uninformed criticism of the North Americans. Canada has lavish hydro sources which provide 12% of its primary energy from this renewable source. The USA, with 4.5% of the world population, uses one-quarter of all the world's energy but is generously endowed with abundant coal, natural gas and oil. One could argue that the North Americans are burning their own fuel. But are they wise to burn it at the present rates of

Table 2.3. Primary energy consumption by fuel [3].



oil natural gas coal nuclear energy hydroelectricity **primary energy**

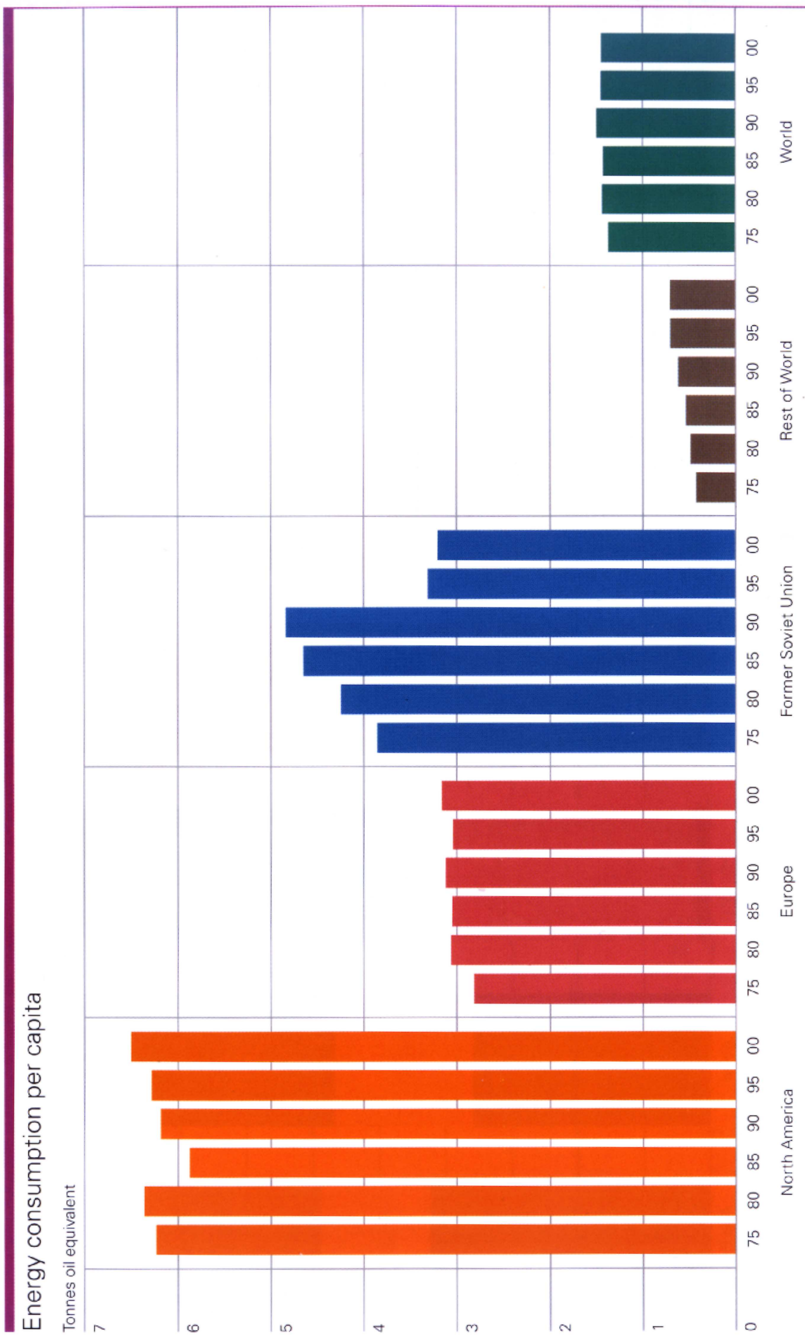
Consumption by fuel*

	1999						2000					
Million tonnes oil equivalent	Oil	Natural gas	Coal	Nuclear energy	Hydro-electricity	Total	Oil	Natural gas	Coal	Nuclear energy	Hydro-electricity	**Total**
USA	888.9	561.7	546.4	197.8	27.2	2222.0	897.4	588.9	564.1	204.7	23.4	**2278.6**
Canada	82.9	65.4	27.8	19.0	29.6	224.6	82.9	70.1	29.3	18.7	30.8	**231.8**
Mexico	80.8	30.6	6.0	2.6	2.8	122.8	84.3	32.0	6.1	1.8	3.2	**127.4**
Total North America	1052.6	657.7	580.2	219.4	59.6	2569.4	1064.6	691.0	599.5	225.2	57.4	**2637.8**
Argentina	20.8	30.4	0.7	1.8	1.9	55.6	20.1	29.8	0.7	1.6	2.0	**54.1**
Brazil	83.2	6.4	11.7	1.0	25.2	127.5	84.4	8.5	12.2	1.4	26.2	**132.7**
Chile	11.7	3.6	4.3	–	1.2	20.7	11.8	5.2	3.5	–	1.6	**22.1**
Colombia	10.6	4.7	2.1	–	2.9	20.3	10.5	5.3	2.2	–	2.6	**20.6**
Ecuador	6.0	0.1	–	–	0.6	6.7	6.5	0.1	–	–	0.7	**7.2**
Peru	7.4	0.5	0.5	–	1.2	9.5	7.0	0.4	0.5	–	1.3	**9.2**
Venezuela	21.9	24.1	0.3	–	5.2	51.5	22.6	24.5	0.3	–	5.5	**52.9**
Other S. & Cent. America	55.1	9.3	0.5	–	6.7	71.6	55.8	9.7	0.5	–	6.8	**72.8**
Total S. & Cent. America	216.7	79.1	20.1	2.8	44.9	363.4	218.7	83.5	19.9	3.0	46.7	**371.6**
Austria	12.1	7.2	3.2	–	3.6	26.1	11.5	7.1	3.0	–	3.7	**25.4**
Belgium & Luxembourg	32.4	13.3	6.9	12.7	0.2	65.4	33.1	13.4	7.3	12.7	0.2	**66.7**
Bulgaria	4.9	2.8	6.6	3.9	0.2	18.6	5.0	2.8	6.5	4.9	0.3	**19.5**
Czech Republic	8.2	7.7	17.1	3.4	0.2	36.7	7.9	7.7	19.3	3.5	0.2	**38.6**
Denmark	10.6	4.5	4.7	–	†	19.9	10.4	4.4	4.0	–	†	**18.8**
Finland	10.7	3.3	3.6	6.0	1.1	24.6	10.5	3.4	3.5	6.2	1.3	**24.9**
France	96.4	33.9	14.2	101.9	6.6	253.0	95.1	35.6	14.0	107.3	6.2	**258.2**
Germany	132.4	72.1	80.2	43.9	2.0	330.6	129.5	71.3	82.7	43.8	2.1	**329.4**
Greece	18.7	1.2	8.8	–	0.4	29.1	19.1	1.5	8.9	–	0.3	**29.8**
Hungary	7.1	9.9	3.4	3.6	†	24.1	6.9	9.6	3.2	3.7	†	**23.4**
Iceland	0.9	–	0.1	–	0.5	1.5	0.9	–	0.1	–	0.5	**1.6**
Republic of Ireland	8.3	3.0	1.6	–	0.1	13.1	8.3	3.4	1.7	–	0.1	**13.5**
Italy	94.4	56.0	11.6	–	3.9	165.9	93.0	57.4	11.7	–	3.8	**166.0**
Netherlands	40.6	34.1	7.0	1.0	†	82.7	41.8	34.5	7.9	1.0	†	**85.1**
Norway	10.1	3.2	0.7	–	10.5	24.4	9.4	3.5	0.7	–	12.2	**25.8**
Poland	19.9	9.3	61.0	–	0.4	90.5	20.6	10.0	57.1	–	0.4	**88.0**
Portugal	15.4	2.0	3.6	–	1.1	22.2	15.3	5.4	3.6	–	1.1	**25.5**
Romania	9.5	15.5	6.7	1.3	1.6	34.5	8.9	14.6	8.4	1.4	1.3	**34.5**
Slovakia	3.0	5.8	4.8	3.4	0.4	17.4	2.8	5.1	4.7	4.3	0.4	**17.2**
Spain	68.4	13.5	20.5	15.2	2.6	120.2	70.1	15.2	21.6	16.0	3.1	**125.9**
Sweden	16.1	0.8	2.0	18.9	6.2	43.9	15.2	0.8	2.0	14.8	6.8	**39.6**
Switzerland	12.6	2.4	0.1	6.4	3.5	25.1	12.2	2.4	0.1	6.8	3.3	**24.8**
Turkey	29.5	10.8	27.7	–	3.0	71.0	31.5	12.7	27.2	–	2.7	**74.1**
United Kingdom	79.4	82.8	35.6	24.8	0.7	223.4	77.6	86.1	37.7	24.0	0.7	**226.1**
Other Europe	16.3	4.6	10.1	1.2	2.7	35.0	16.0	5.0	10.5	1.2	2.7	**35.4**
Total Europe	757.9	399.7	341.8	247.6	51.5	1798.9	752.6	412.9	347.4	251.6	53.4	**1817.8**
Azerbaijan	6.3	5.0	–	–	0.1	11.5	7.4	4.9	–	–	0.1	**12.4**
Belarus	6.1	13.8	0.1	–	†	20.0	5.4	14.6	0.1	–	†	**20.1**
Kazakhstan	6.0	7.1	19.8	–	0.6	33.6	6.2	7.2	23.2	–	0.6	**37.2**
Lithuania	3.1	2.2	0.1	2.5	0.1	8.0	2.9	2.4	0.1	2.2	0.1	**7.7**
Russian Federation	126.2	326.4	109.4	30.9	13.8	606.8	123.5	339.5	110.4	33.7	14.2	**621.3**
Turkmenistan	4.5	10.2	–	–	–	14.7	4.8	11.3	–	–	–	**16.1**
Ukraine	13.3	63.6	38.5	18.6	1.0	135.0	10.4	61.6	38.8	19.9	0.9	**131.7**
Uzbekistan	7.1	44.3	1.8	–	0.6	53.8	6.8	44.8	1.6	–	0.6	**53.8**
Other Former Soviet Union	4.7	7.1	1.0	0.6	3.1	16.4	5.7	7.1	0.8	0.5	3.1	**17.2**
Total Former Soviet Union	177.3	479.7	170.7	52.6	19.3	899.8	173.1	493.4	175.0	56.3	19.6	**917.5**
Iran	58.4	49.5	1.0	–	0.4	109.3	56.9	56.6	1.1	–	0.4	**115.0**
Kuwait	8.6	7.8	–	–	–	16.4	8.0	8.6	–	–	–	**16.7**
Qatar	1.1	14.3	–	–	–	15.4	1.1	13.0	–	–	–	**14.2**
Saudi Arabia	60.9	41.6	–	–	–	102.5	62.4	42.3	–	–	–	**104.7**
United Arab Emirates	13.0	28.3	–	–	–	41.3	14.3	30.0	–	–	–	**44.3**
Other Middle East	65.0	19.1	5.7	–	0.3	90.1	66.3	19.5	6.2	–	0.3	**92.3**
Total Middle East	207.0	160.6	6.7	–	0.7	375.0	209.0	170.0	7.3	–	0.7	**387.2**
Algeria	8.1	20.0	0.3	–	†	28.4	8.5	21.9	0.3	–	†	**30.7**
Egypt	27.8	12.9	0.9	–	1.1	42.7	26.2	16.1	0.9	–	1.1	**44.3**
South Africa	21.8	–	82.1	3.5	0.3	107.7	22.5	–	81.9	3.5	0.3	**108.3**
Other Africa	58.2	14.0	6.8	–	4.9	83.9	59.5	14.9	6.6	–	5.1	**86.1**
Total Africa	115.9	46.9	90.1	3.5	6.3	262.7	116.7	52.9	89.7	3.5	6.5	**269.4**
Australia	38.0	17.8	45.5	–	1.5	102.8	38.7	19.1	46.7	–	1.4	**106.0**
Bangladesh	3.2	7.5	0.2	–	0.1	10.8	3.3	9.3	0.2	–	0.1	**12.8**
China	207.2	19.3	512.7	3.8	16.8	759.7	226.9	22.3	480.1	4.3	19.0	**752.7**
China Hong Kong SAR	9.3	2.4	3.9	–	–	15.6	9.6	2.2	3.7	–	–	**15.5**
India	95.2	21.4	154.5	3.3	7.1	281.5	97.6	22.5	163.4	4.1	6.6	**294.2**
Indonesia	46.8	24.8	10.5	–	0.8	82.9	51.1	25.0	11.5	–	0.8	**88.4**
Japan	257.3	67.1	91.5	82.0	8.0	505.9	253.5	68.6	98.9	82.5	7.9	**511.3**
Malaysia	20.3	17.1	1.2	–	0.4	39.0	20.5	19.5	1.3	–	0.4	**41.7**
New Zealand	6.3	4.7	1.2	–	2.0	14.1	6.3	4.9	1.2	–	2.1	**14.4**
Pakistan	18.2	15.6	2.1	†	1.8	37.7	19.6	17.1	2.1	0.1	1.6	**40.4**
Philippines	18.0	†	2.9	–	0.7	21.6	16.8	†	4.3	–	0.7	**21.7**
Singapore	28.3	1.4	–	–	–	29.6	29.1	1.4	–	–	–	**30.4**
South Korea	99.7	16.8	38.2	26.6	0.5	181.9	101.8	18.9	42.9	28.1	0.5	**192.3**
Taiwan	39.9	5.6	24.9	9.9	0.8	81.1	39.8	6.2	28.9	9.9	0.8	**85.5**
Thailand	35.4	15.6	7.9	–	0.3	59.2	34.1	18.8	8.4	–	0.5	**61.8**
Other Asia Pacific	18.6	4.4	53.1	–	3.5	79.6	20.2	4.5	53.6	–	3.7	**82.0**
Total Asia Pacific	941.7	241.5	950.3	125.6	44.3	2303.0	968.9	260.3	947.2	129.0	46.1	**2351.1**
TOTAL WORLD	**3469.1**	**2065.2**	**2159.9**	**651.5**	**226.6**	**8572.2**	**3503.6**	**2164.0**	**2186.0**	**668.6**	**230.4**	**8752.4**
of which: OECD	2178.1	1135.1	1070.2	565.8	118.2	5067.5	2184.8	1187.9	1106.5	575.6	118.0	**5173.0**
European Union 15	635.9	327.7	203.5	224.4	28.5	1420.1	630.5	339.5	209.6	225.8	29.4	**1434.9**
Other EMEs‡	1079.8	421.7	890.8	23.3	84.2	2499.4	1112.7	455.2	874.4	24.9	88.1	**2555.3**

*In this Review, primary energy comprises commercially traded fuels only. Excluded, therefore, are fuels such as wood, peat and animal waste which, though important in many countries, are unreliably documented in terms of consumption statistics.

†Less than 0.05.

‡Excludes Central Europe and Former Soviet Union.



Energy consumption per capita at the global level has shown almost no growth over the last 20 years. Per capita consumption in North America remains at more than twice the levels of Europe and the Former Soviet Union and at almost 10 times the level in the Rest of World.

Fig. 2.7. Energy consumption per capita, 1975–2000 [3].

Table 2.4. Primary energy consumption, population and GNP.

Country	**Energy Consumption 1999**			**Population**		**GNP/Capita (3)**
	mtoe (1)	% World Total	Per capita (toe/yr)	Millions (2)	%World Total	1998 US Dollars
Algeria	29.2	0.3	0.93	31.47	0.52	1550
Australia	102.8	1.2	5.42	18.97	0.313	20,050
Argentina	57.9	0.7	1.58	36.58	0.604	7600
Belgium	65.1	0.8	6.48	10.16	0.168	24,510
Brazil	127.4	1.5	0.78	163.95	2.71	4420
Canada	227.8	2.7	7.47	30.49	0.504	19,320
China	752.6	8.8	0.59	1,277,558	21.1	780
Denmark	19.9	0.2	3.76	5.29	0.087	32,030
Egypt	42.7	0.5	0.685	62.3	1.03	1400
France	252.4	3.0	4.27	59.08	0.976	23,460
Germany	330.9	3.9	4.02	82.22	1.36	25,350
Greece	28.8	0.3	2.7	10.65	0.176	11,770
Hungary	24	0.3	2.39	10.04	0.166	4650
India	276.4	3.2	0.273	1,013,662	16.74	450
Indonesia	79.6	0.9	0.375	212.11	3.5	580
Iran	111.2	1.3	1.66	67.7	1.12	-
Ireland	13	0.1	3.48	3.73	0.062	19,160
Italy	165.8	1.9	2.9	57.23	0.945	19,710
Japan	507.4	6.0	3.99	127	2.1	32,230
Malaysia	38	0.4	1.69	22.45	0.371	3400
Mexico	124.6	1.5	1.25	99.63	1.645	4400
Netherlands	83.7	1.0	5.3	15.79	0.261	24,320
New Zealand	13.7	0.2	3.55	3.86	0.064	13,780
Norway	24.7	0.3	5.53	4.465	0.074	32,880
Pakistan	37.2	0.4	0.238	156.45	2.58	470
Poland	92.6	1.1	2.39	38.76	0.64	3960
Portugal	22.1	0.3	2.24	9.88	0.163	10,600
Romania	34	0.4	1.52	22.33	0.369	1500
Russian Fed.	607.8	7.1	4.14	146.9	2.43	2270
Saudi Arabia	104.1	1.2	4.82	21.6	0.357	6910
Singapore	29.6	0.4	9.19	3.57	0.059	29,610
S. Africa	107.7	1.3	2.49	43.28	0.715	3160
S. Korea	182	2.1	3.84	47.44	0.783	8490
Spain	119.1	1.4	3.0	39.63	.0654	14000
Sweden	42.9	0.5	4.81	8.91	0.147	25040
Switzerland	25	0.3	3.38	7.39	0.122	38350
Taiwan	81	1.0	3.63	22.32	0.369	---
Thailand	59.3	0.7	0.963	61.6	1.017	1960
Turkey	76.2	0.9	1.28	59.6	0.984	2900
United Arab Emirates	46	0.5	15.65	2.94	0.049	17870
UK	222.4	2.6	3.78	58.83	0.972	22640
Ukraine	137	1.6	2.71	50.5	0.834	750
USA	2205	25.8	8.09	272.6	4.5	30600
Venezuela	56	0.7	2.3	24.4	0.403	3670
World	8533.6	100	1.41	6055049	100	4890

(1) BP Statistical Review of World Energy, June 2000

(2) International Marketing Data and Statistics 2001 (25th Ed.), London , UK, 2000

(3) World Development Indicators, World Bank, 2000.

consumption? In the event, the USA generated (in 2000) a national productivity at 6.3 times the world average value by using energy at 5.74 times the world average value.

One of the challenges of the energy future is that many of the world's poorest countries are not on the energy-GNP grid, Fig. 2.8, at all. Moreover, China and India, with 38% of the world population between them, have so far achieved little per

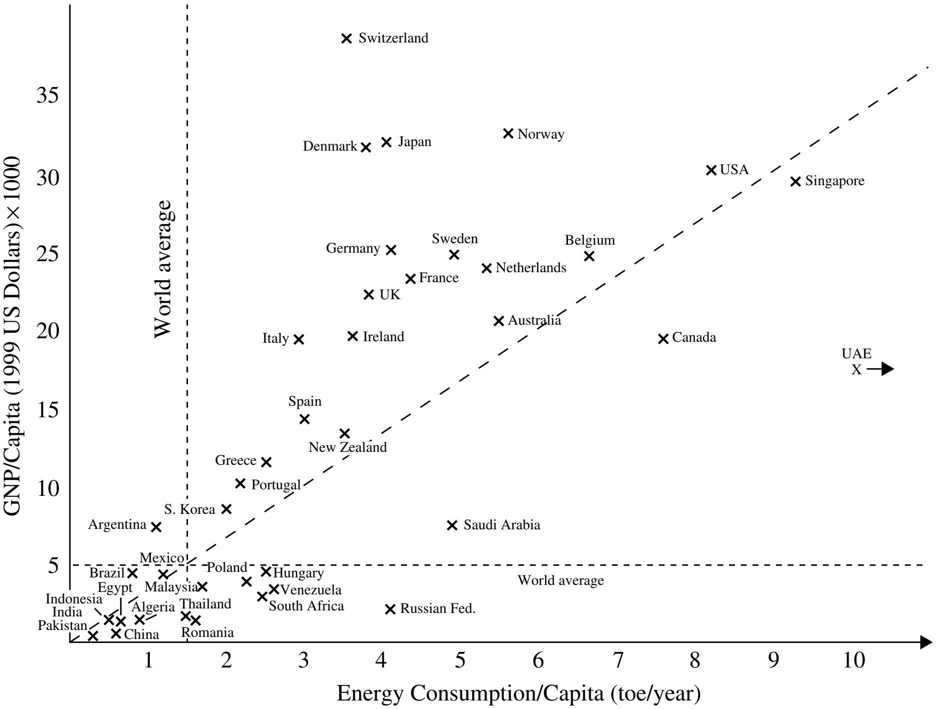


Fig. 2.8. GNP/capita versus energy consumption/capita.

capita economic performance. All the recent signs indicate, however, that China, which has abundant coal supplies, is about to make a great surge forward.

Available forecasts of the future indicate that the world population, energy consumption and Gross Domestic Product (GDP) will all continue to increase, Fig. 2.9 [4]. The GDP is not the same as the GNP of Fig. 2.8 but is also an indicator of industrial development and national prosperity. If the forecast of Fig. 2.9 proves to be correct, then GDP/capita will rise faster than the growth of population.

Most of the countries that have achieved high economic prosperity have done so by the extravagant use of industrial energy, especially fossil fuels. Fast-developing countries like Malaysia and Singapore are attempting to do the same. The poor and underdeveloped countries of the world may never have this opportunity because there is not enough primary fossil energy. Also, oil-rich countries like Saudi Arabia, Kuwait and the United Arab Emirates (UAE), which could fund energy development in the Third World, are reluctant to lend large sums of money on a long-term, speculative basis — they prefer safe and short-term investments in the USA and Europe. Nevertheless, there is abundant renewable energy for all and for ever. The world problem is not an energy supply problem but a human behaviour problem.

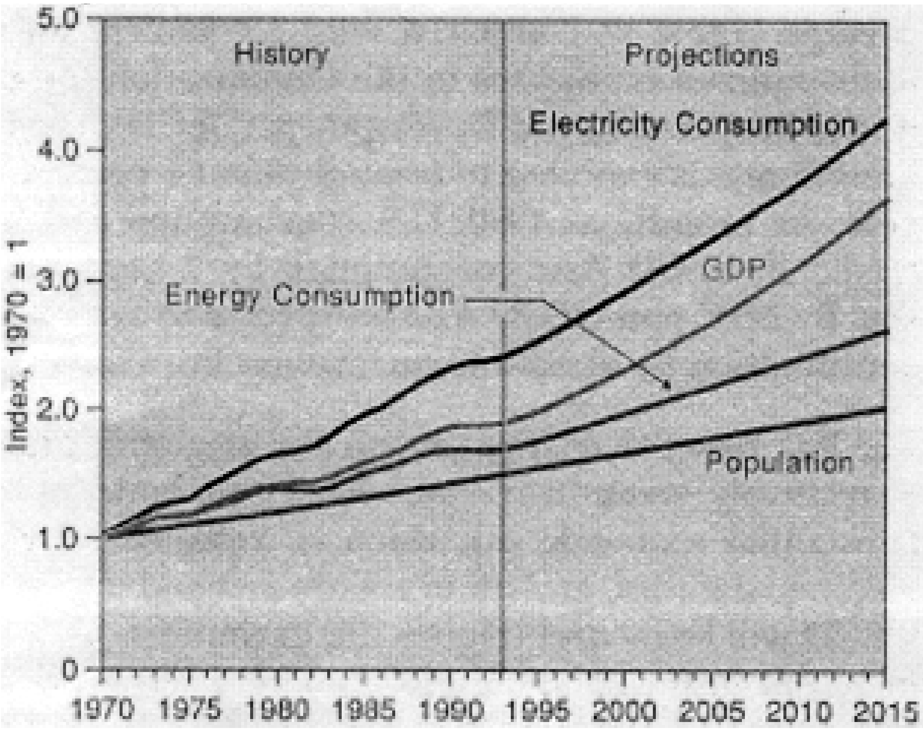


Fig. 2.9. World energy, GDP and population trends, 1970–2015 [4].

Table 2.5. UK primary energy consumption (mtoes) [6].

Year	Coal (3)	Oil (8)	Natural Gas (5)	Nuclear Energy	Hydro Electricity (6)	Total (2)
1973	83.2	104.2	28.0	7.5	0.3	232.2
1978	70.4	94	37.9	7.9	1.2	211.4
1982	65.1	65.4	42.2	9.4	1.4	183.5
1988	65.9	79.2	47.9	13.5	1.4	207.9
1990	65.6	82.9	47.2	17	0.6	212.6
1993	53.3	84	57.8	23.1	0.5	218.7
1996	44.8	83.9	73.9	24.4	0.4	227.4
1999	35.8	78.7	82.5	24.8	0.6	222.4
2000	37.7	77.6	86.1	24.0	0.7	226.1
Share of 2000 total	16.7%	34.3%	38.1%	10.6%	0.31%	100%

2.5.2. *Energy production and use in the UK*

The changes in primary fuel consumption in the UK since 1973 are summarised in Table 2.5 and illustrated by the graph of Fig. 2.10. Coal consumption has slowly declined since the early 1970s while natural gas consumption has slowly increased. After the peak figures of the early 1970s, oil consumption declined for about 10 years but has now levelled out to about 36% of the total demand. Nuclear-generated electricity now (2002) accounts for 11% of the total energy consumption.

A feature that has recently occurred is that electricity is now imported from France using undersea cables beneath the English Channel. Like all generated electricity it is a secondary fuel, probably obtained from nuclear generation.

The contribution of natural-flow hydro power increases only slowly as wind energy stations come on-stream. All of the available natural hydro sites have been exploited. Vast schemes such as the possible Severn Barrage hydro scheme (see Chapter 9) would make a big contribution but would be classed as man-made hydro power.

Comparison of the UK figures for primary energy production, Table 2.6, with those for primary energy consumption, Table 2.5, shows a number of interesting features.

The flow of UK energy from source to end users is illustrated in Fig. 2.11. Most of the primary fuel input was converted to heat and thence to mechanical or/and electrical energy. Iron and steel, once a UK base industry and massive energy user, has shrunk to a fraction of its size 30 years ago. The UK industry sector is now smaller than the domestic sector while transport accounts for almost one-quarter of all the end user energy.

Table 2.6. UK primary energy production (mtoes) [6].

Year	Coal (3)	Oil (8)	Natural Gas (5)	Nuclear Energy	Hydro Electricity (6)	Total (2)
1973	82.6	0.4	27.2	7.5	0.3	118.1
1978	76.1	53.3	33.7	7.9	0.4	171.4
1982	73.4	103.4	32.4	9.4	0.4	220.0
1988	63.3	114.5	38	16.4	0.6	232.8
1990	56.4	91.6	40.9	17	0.6	206.7
1993	41.5	100.2	54.3	23.1	0.5	219.6
1996	30.5	129.7	76.1	24.4	0.4	161.1
1999	22.8	137.1	89.7	24.8	0.5	275
2000	19.5	126.2	97.3	24.0	0.7	267.7
Share of 2000 total	7.3%	47.1%	36.3%	9%	0.26%	100%

(2) includes solar and geothermal heat
(3) includes solid renewables (wood, straw, waste, etc.)
(4) crude oil plus NGLs and primary feedstocks
(5) includes colliery methane, landfill gas and sewage gas
(6) natural flow hydro plus wind stations
(8) adjusted for stock change and net trade in derived products

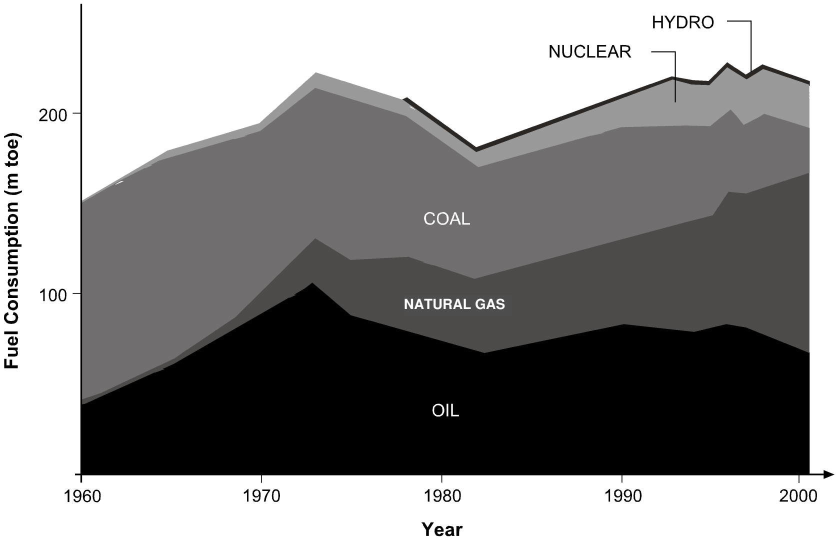


Fig. 2.10. Primary energy consumption in the UK [1, 6].

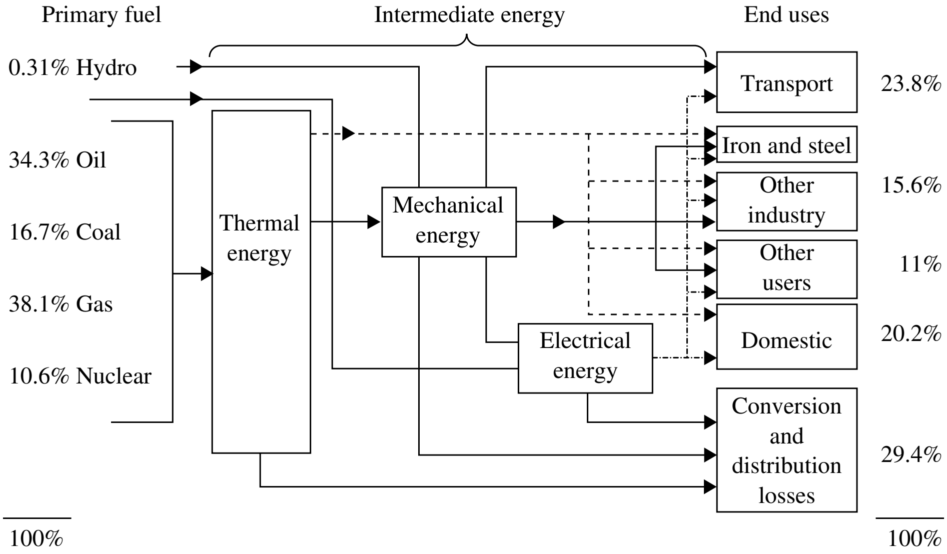

Primary fuel
Intermediate energy
End uses
0.31% Hydro
34.3% Oil
16.7% Coal
38.1% Gas
10.6% Nuclear
100%
Thermal energy
Mechanical energy
Electrical energy
Transport
Iron and steel
Other industry
Other users
Domestic
Conversion and distribution losses
23.8%
15.6%
11%
20.2%
29.4%
100%

Fig. 2.11. UK energy flows 2000 (excluding exports and non-energy uses) [adapted from Ref. 2 using data from Ref. 7].

The UK is one of the few OECD countries in which the production of primary energy exceeds the consumption, making it a net exporter, as shown in Fig. 2.12. This is due to the highly productive oil and natural gas fields in the North Sea and other coastal areas, which are further discussed in Chapters 5 and 6.

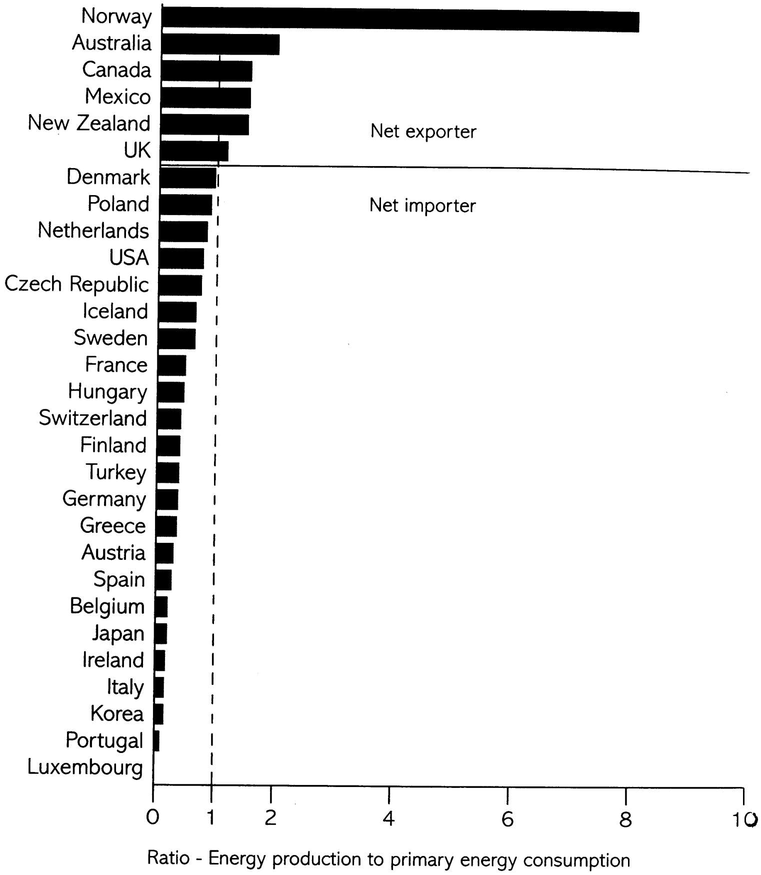


Fig. 2.12. Ratio of energy production to primary energy consumption in OECD countries, 1998 [8]. Source: International Energy Agency.

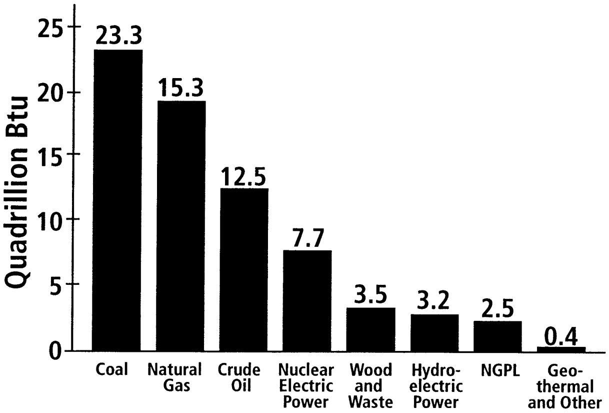


Fig. 2.13. US energy production in 1999 [9].

For example, in 2000, 18.32/37.7 or 48% of the coal used in Britain was imported. This represents a useful saving of the base stock of coal and is therefore conservation achieved. But it also demonstrates the decline of coal production — once one of the country's base industries.

The columns representing oil in Tables 2.5 and 2.6 also show interesting features. In 1973 virtually all UK oil was imported. By 1980 the country was self-sufficient in oil and a net exporter by 2000. For example, in 2000, in mtoe units,

$$\frac{\text{Oil production} - \text{oil consumption}}{\text{Oil production}} = \frac{126.2 - 77.6}{126.2} = 38.5\%$$

The excess of production over consumption was (by implication) exported.

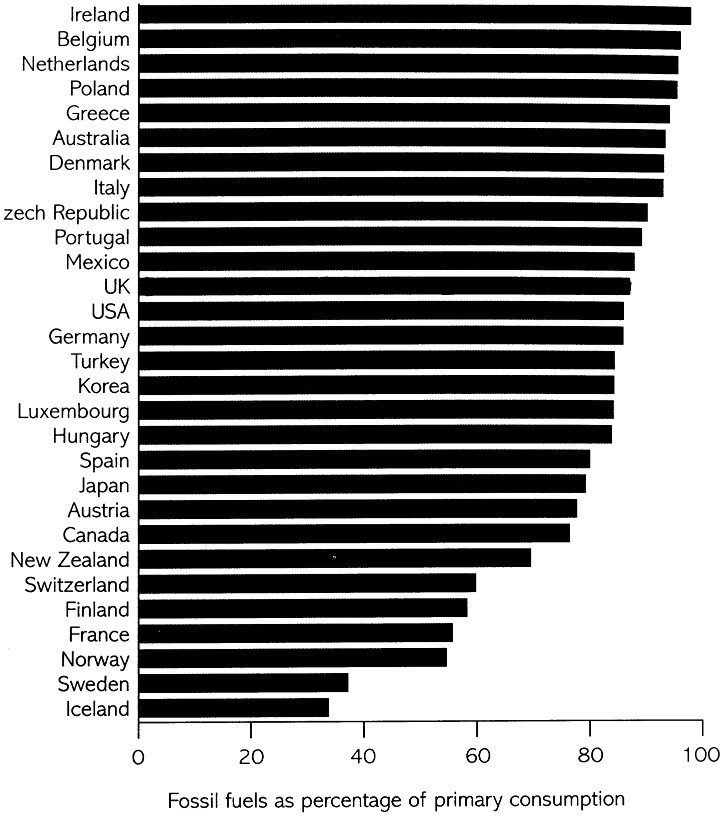


Fig. 2.14. Fossil fuel dependency in OECD countries, 1998 [8]. Source: International Energy Agency.

2.5.3. *Energy production and use in the USA*

Energy production in the USA for 1999 in BTU is shown in the bar chart, Fig. 2.13, broken down by energy sources [9]. The fossil fuels coal, natural gas, oil and natural gas plant liquids (NBPL) account for almost 80% of the total. The corresponding value in Fig. 2.14 of 84.1% is slightly different from Fig. 2.13 because the ratio of fossil fuels to total primary fuels there excludes data incorporated for wood and waste plus geothermal.

Since the late 1950s the energy consumption in the USA has exceeded the production, Fig. 2.15, mainly driven by the demand for petroleum. In 1999 the US

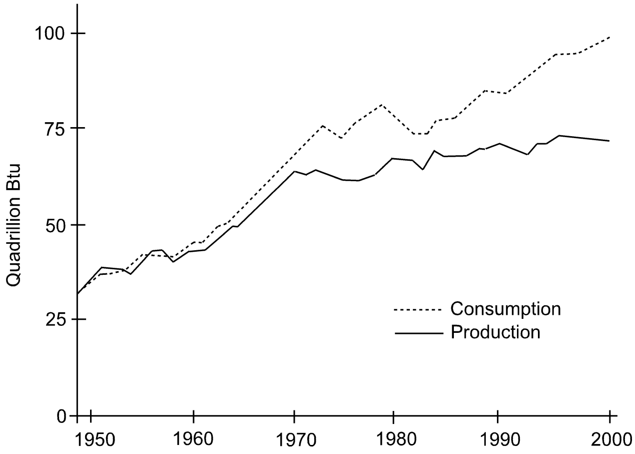


Fig. 2.15. US energy production and consumption [9].

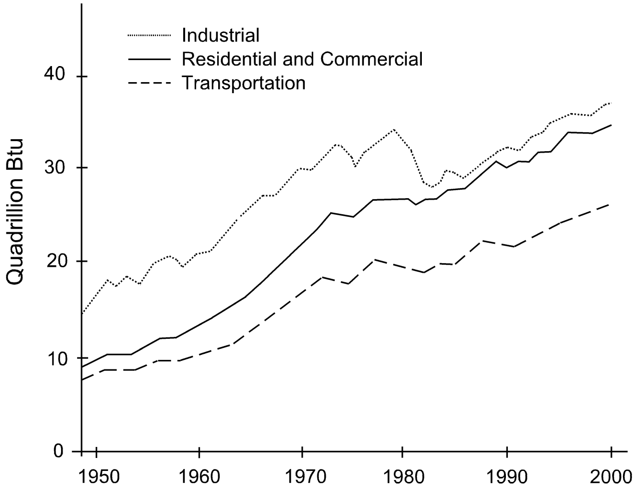


Fig. 2.16. US energy consumption by end-user sector [9].

produced 73 quadrillion BTU of energy and exported 4 quadrillion BTU, about 40% of it as coal. Consumption totalled 97 quadrillion BTU, requiring imports of 27 quadrillion BTU, which is 18 times the 1949 figure.

In the USA the industrial sector is the largest sector consumer, but all sectors continue to demand more energy, Fig. 2.16. Industrial demand continues to be dominated by oil and natural gas, Fig. 2.17 [9]. The use of coal, once the leading source, continues to decline, as it does also in the residential and commercial sectors.

About three fifths of the energy consumed in the industrial sector is used for manufacturing. The remainder goes to mining, construction, agriculture, fisheries and forestry. Within manufacturing, large consumers of energy are the petroleum and coal products, chemicals and allied products and primary metal industries. Natural gas is the most commonly consumed energy resource in manufacturing. The predominant end-use activity is process heating, followed by machine drives and then facility heating, ventilation and air conditioning combined.

Just under 7% of all energy consumed in the USA is used for non-fuel purposes, such as asphalt and roads, oil for roofing products and road building and conditioning, liquefied petroleum gases for feed stocks and petrochemical plants, waxes for packaging, cosmetics, pharmaceuticals, inks, and adhesives and still gas for chemical and rubber manufacture.

While variety and change in energy sources are the hallmarks of the industrial sector and the residential and commercial sector, transportation's reliance on petroleum has been nearly total since 1949 [9]. The enormous appetite for energy of the USA is illustrated in the energy per capita bar chart of Fig. 2.18. Americans use energy at almost three times the rate of Europeans.

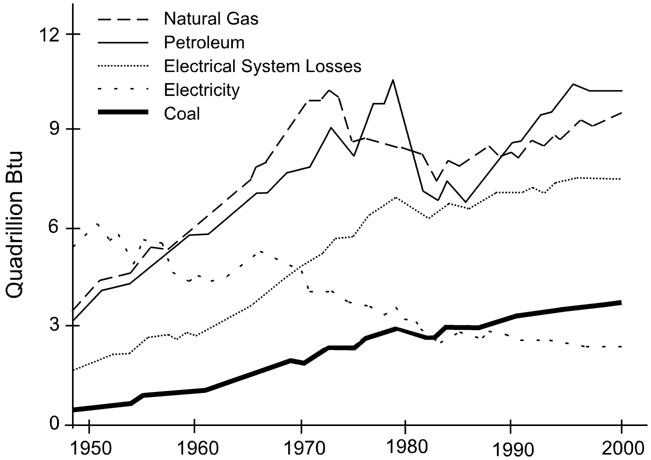


Fig. 2.17. US industrial energy consumption [9].

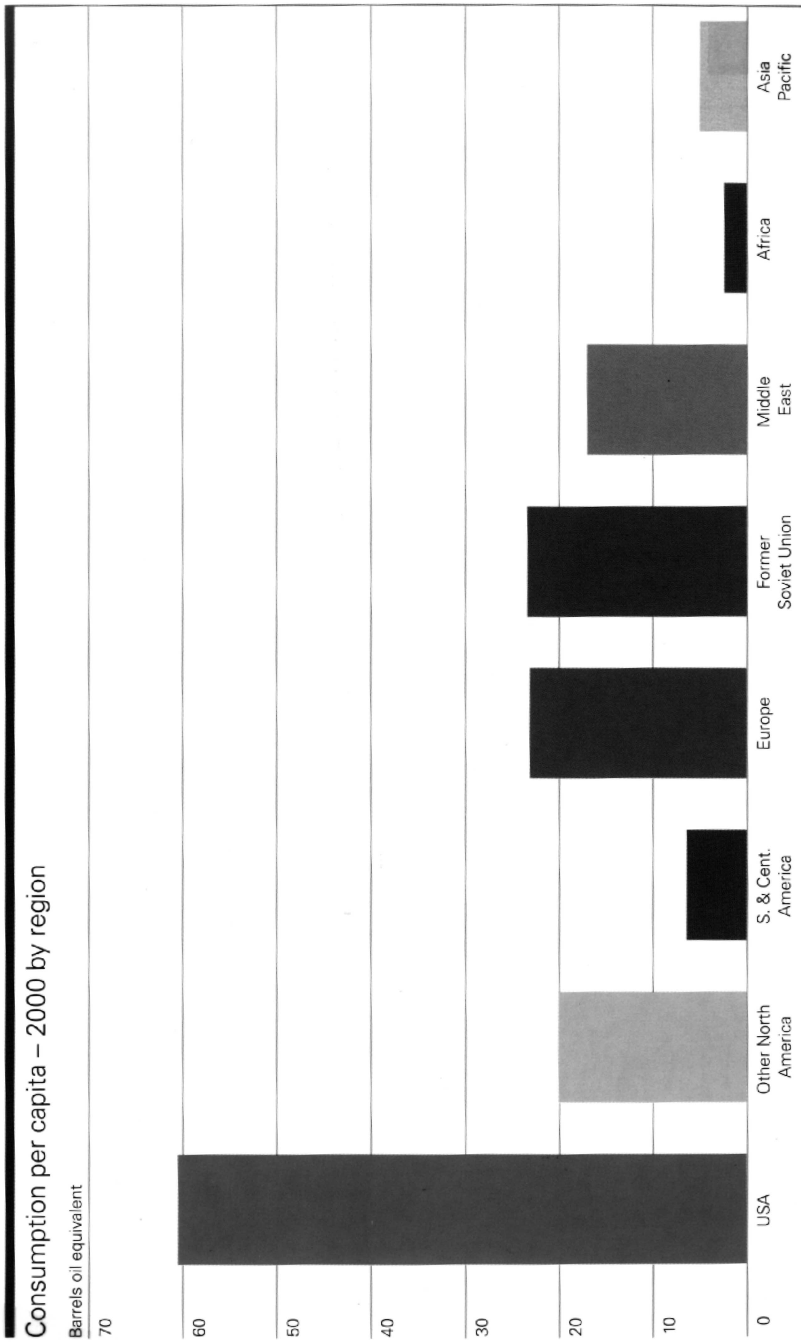


Fig. 2.18. Energy consumption per capita, 2000 [3].

2.5.4. *World fossil fuel production and consumption*

Production figures for the world's leading fossil fuel producers are listed in Table 2.7 for the year 2000. The USA produces more oil than any country other than Saudi Arabia and dominates the world energy market, both as a producer and a consumer.

Table 2.7. Fossil fuel production in 2000 (mtoes) [3].

Country	**Oil**	**Natgas**	**Coal**	**Total**
USA	353	500	570.7	1423.7
Russian Fed	323.3	490.5	115.8	929.6
China	162.3	25	498	685.3
Saudi Arabia	441.2	42.3	-	483.5
Canada	126.3	151	37.2	314.5
UK	126.2	97.3	19.5	243
Iran	186.6	54.2	-	240.8
Australia	35.5	28	155.6	217.1
India	36.5	23.5	154.3	214.3
Mexico	172.1	32.3	5.3	209.7
Norway	152.5	47.2	-	199.7
Venezuela	166.8	24.5	5.6	196.9
Indonesia	67.8	57.5	47.3	172.6
Unt. Arab Emirates	114.7	35.9	-	150.6
Algeria	67	80.4	-	147.4
Nigeria	103.9	9.9	-	113.8

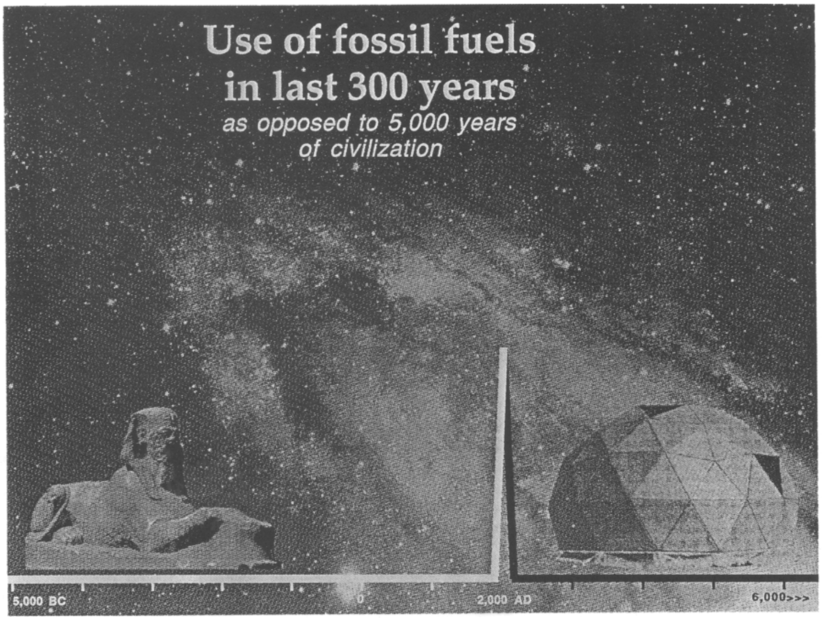

Use of fossil fuels
in last 300 years
as opposed to 5,000 years
of civilization
5,000 BC
0
2,000 AD
6,000>>>

Fig. 2.19. Time scale of the fossil fuel era.

Most of the OECD countries consume more primary energy than they produce and are net importers of energy, as shown in Fig. 2.12 [8].

The OECD countries are largely dependent for their energy needs on fossil fuels, as shown in the bar chart of Fig. 12.13 [9]. Of the present 29 OECD countries (2002) only two supply more than 50% of their primary energy consumption from non-fossil sources. The oil producer countries of OPEC also are net exporters and would be included in the exporter category if Fig. 2.12 was extended as a whole world listing.

A historical perspective of the fossil fuel era is demonstrated in the time scale of Fig. 2.19. The mass use of fossil fuels began in Europe during the 18th century (1700s). There was no mass fossil fuel use before the Industrial Revolution in Britain or elsewhere. Once the fossil fuels have been largely depleted there can never be another fossil fuel era. The present period of fuel history is unique. It is conjectural to put a firm date to the end of the fossil fuel era but it is likely that virtually all of the usable oil and natural gas will be finished in less than 100 years. Most of the coal will be finished in less than 300 years from now. In a long-term historical perspective the world fossil fuel era is represented by the triangular blip in Fig. 2.19. The apex of the triangle roughly coincides with the turn of the 21st century. Is the end of the fossil fuel era, especially the ending of natural crude oil supplies, sufficiently near to engage the attention and action of the nations and peoples of the world?

2.6. Risks Associated with Energy Systems

All energy systems entail risks. Some risks affect public health and welfare directly. Other risks affect the environment and have direct or indirect ecological impact. The extraction, transportation, distribution and use of prime fuels, especially fossil fuels, create some environmental and ecological side effects that may be not only undesirable but dangerous to human life and welfare. Risk assessment, as applied to energy systems, is unreliable, subjective and controversial. No attempt is made here to apportion different risks in a quantitative or even relative manner. The approach is to note the main areas for concern. Different observers may reach very different conclusions as to the relative seriousness of the various features delineated.

Features of the risks associated with energy production and use are discussed under the headings listed below [10].

2.6.1 Industrial accidents and industrial diseases
2.6.2 Large-scale accidents and sabotage
2.6.3 Management of energy waste
2.6.4 Ecosystem effects
2.6.5 Water supply problems
2.6.6 Emissions

2.6.1. *Industrial accidents and industrial diseases*

Industrial accidents and industry-induced diseases are well recorded and can therefore be assessed fairly accurately. From the accidental death statistics, coal mining is the most dangerous form of fuel procurement, resulting in more fatalities than oil, gas and nuclear energy together.

In the UK, before the Second World War (i.e. in the 1930s), the toll in the deep coal mines was about 50 fatalities per year. This appalling record was greatly reduced by post-war modernisation of the coal industry and is now (2002) further reduced by the drastic contraction of the industry. Corresponding reductions have occurred in the incidence of industrial injuries and lung diseases caused by mining gases and coal dust.

2.6.2. *Large-scale accidents and sabotage*

Risks exist of low probability, high consequence accidents associated with nuclear reactors, hydroelectric dams, and the transportation and storage of liquified natural gas (LNG). Between 1918 and 1958 there were an average of 40 deaths per year from dam failures in the USA, including some high casualty individual failures. These figures are comparable with the fatality figures from the British coal industry in the same period and both have been significantly reduced in the past 30 years. Worst case scenarios for both dams and LNG facilities suggest numbers of casualties comparable with those anticipated from severe nuclear accidents. An important difference is that casualties from dam failures, oil field fires and explosions and LNG accidents are immediate and obvious. By comparison, nuclear accidents may cause delayed effects that affect a large number of people and therefore engender a greater public apprehension.

In 1988 an explosion and fire on an offshore oil platform in the North Sea killed 167 people. This was the worst single energy-industry incident in recent times, emphasising the fact that even industries considered low-risk by the public exact a death toll on their workers.

Industrial plants are always vulnerable to sabotage. Nuclear plants tend to be better-guarded than dams or LNG refineries. A discussion of this issue is included in Chapter 8.

2.6.3. *Management of energy waste*

All energy systems produce waste. The management of industrial wastes involves risks to health and poses environmental concerns. In the developed industrial countries the transportation, processing and disposal of industrial wastes is highly developed and the subject of safe and reliable control procedures. Waste management relevant to individual fossil fuels and biofuels is discussed in appropriate chapters below. The issue of radioactive waste management is treated as a special case in Chapter 8.

2.6.4. *Ecosystem effects*

Energy production and use has some adverse ecological effects, including the loss of arable land, water resources, natural beauty, open space, habitat, wildlife preservation and wilderness areas. The relative importance that might be attached to these various criteria, in comparison with the universal need for energy, is very much a feature of individual opinion. Loss of ecological diversity has long-range human consequences that are not well understood compared with the more immediate effects of energy development.

It is difficult to assign quantitative levels to the destructive side effects of different energy systems. From the point of view of ecosystems it is possible that hydroelectric power development, with its "clean" public image, is more destructive per unit of energy output than fossil fuel plants because of the large land area involved. Similarly, the land-based production of biomass can have very serious destructive side effects that are less obvious than those of fossil or nuclear systems.

The ecological side effects of nuclear power are smaller than for any other established energy source. Only if it becomes necessary to deep-mine for low-grade uranium ores will the effects become comparable with coal mining. The widespread use of breeder reactors would eliminate that necessity.

Fossil fuel mining, processing and usage has some very evident ecological effects, depending mainly on the locale. The location of offshore oil rigs, for example, can have significant effects on local marine life. Synthetic oil production from oil shale or coal products would have major ecological impact in pollution and contamination of local groundwater flow.

2.6.5. *Water supply problems*

Fossil fuel and nuclear systems for generating electricity require the availability of large masses of water. Any heat–work energy conversion system, such as a steam turbine or a nuclear reactor, involves a necessary cooling process for which water is most likely used as the coolant fluid. Consequent heating and discharge of the coolant water can have ecological impact. In the choice of site for an electricity-generating station the availability of adequate cooling water supply is a vital consideration. When a station is located on a seashore or lakeshore, the operation of a station may affect the immediate and downstream water turbidity and temperature. If groundwater has to be used at an inland site, this may affect the local hydrological cycle, irrigation, water table levels, water run-off streams and the availability and cost of water for other consumers.

2.6.6. *Emissions*

The combustion of fossil fuels emits a great variety of airborne pollutants. Gaseous pollutants include sulphur oxides, nitrogen oxides, carbon monoxide, carbon dioxide and various hydrocarbons (mainly methane). The gaseous emissions are considered in subsection 2.6.6.2 below. In addition to gaseous emissions, fossil fuel burning gives off solid particles of carbon, some less than 1 mm in size, plus trace amounts of heavy metals. A detailed technical analysis of the effects of carbon particulates is included in subsection 4.4.2.4 of Chapter 4 (coal). A more general summary of gaseous emissions follows here.

Table 2.8. World carbon dioxide emissions, 1990–2020 (million tonnes) [4] (projection assumes high economic growth).

Region/Country	History			Projections				Average Annual Percent Change, 1999-2020
	1990	1998	1999	2005	2010	2015	2020	
Industrialized Countries								
North America	**1,556**	**1,742**	**1,761**	**1,972**	**2,119**	**2,271**	**2,423**	**1.5**
United States[a]	1,345	1,495	1,511	1,690	1,809	1,928	2,041	1.4
Canada	126	146	150	158	165	173	180	0.9
Mexico	84	101	101	124	145	170	203	3.4
Western Europe	**930**	**947**	**940**	**1,005**	**1,040**	**1,076**	**1,123**	**0.9**
United Kingdom	164	154	151	168	177	184	192	1.1
France	102	110	109	116	120	126	135	1.0
Germany	271	237	230	246	252	258	267	0.7
Italy	112	122	121	131	137	141	146	0.9
Netherlands	58	66	64	66	67	69	71	0.4
Other Western Europe	223	260	264	277	287	297	313	0.8
Industrialized Asia	**357**	**412**	**422**	**447**	**461**	**479**	**497**	**0.8**
Japan	269	300	307	324	330	342	353	0.7
Australasia	88	112	115	123	130	137	144	1.1
Total Industrialized	**2,842**	**3,101**	**3,122**	**3,425**	**3,619**	**3,825**	**4,043**	**1.2**
EE/FSU								
Former Soviet Union	1,036	599	607	665	712	795	857	1.7
Eastern Europe	301	217	203	221	227	233	237	0.8
Total EE/FSU	**1,337**	**816**	**810**	**886**	**940**	**1,028**	**1,094**	**1.4**
Developing Countries								
Developing Asia	**1,053**	**1,435**	**1,361**	**1,751**	**2,137**	**2,563**	**3,013**	**3.9**
China	617	765	669	889	1,131	1,398	1,683	4.5
India	153	231	242	300	351	411	475	3.3
South Korea	61	101	107	128	144	159	175	2.4
Other Asia	223	338	343	434	511	595	679	3.3
Middle East	**231**	**325**	**330**	**378**	**451**	**531**	**627**	**3.1**
Turkey	35	50	50	57	66	75	85	2.6
Other Middle East	196	275	280	320	386	456	542	3.2
Africa	**179**	**216**	**218**	**262**	**294**	**334**	**373**	**2.6**
Central and South America	**178**	**246**	**249**	**312**	**394**	**492**	**611**	**4.4**
Brazil	62	87	88	108	139	171	212	4.3
Other Central/South America	116	159	162	204	255	321	399	4.4
Total Developing	**1,641**	**2,222**	**2,158**	**2,703**	**3,276**	**3,920**	**4,624**	**3.7**
Total World	**5,821**	**6,139**	**6,091**	**7,015**	**7,835**	**8,773**	**9,762**	**2.3**
Annex I								
Industrialized	2,758	3,001	3,022	3,301	3,475	3,656	3,841	1.1
EE/FSU	1,132	704	700	761	802	876	930	1.4
Total Annex I	**3,890**	**3,704**	**3,722**	**4,062**	**4,276**	**4,531**	**4,771**	**1.2**

[a] Includes the 50 States and the District of Columbia. U.S. Territories are included in Australasia.

Notes: EE/FSU = Eastern Europe/Former Soviet Union. The U.S. numbers include carbon dioxide emissions attributable to renewable energy sources.

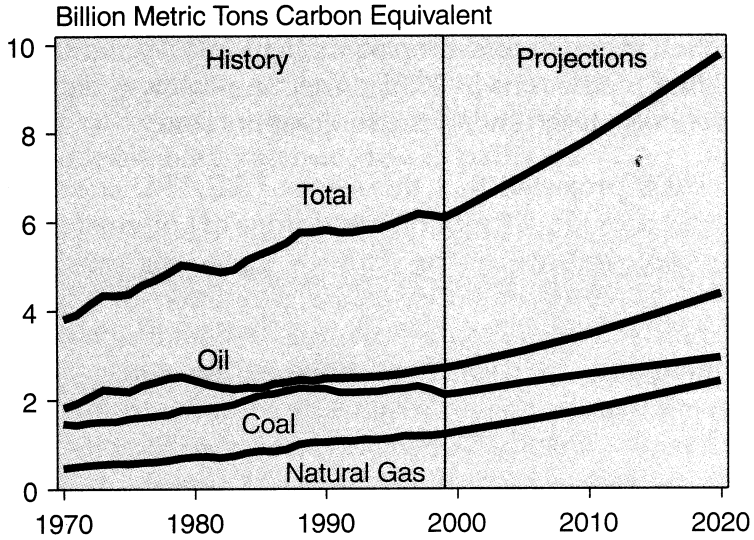
Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 1999*, DOE/EIA-0219(99) (Washington, DC, January 2001). **Projections:** EIA, *Annual Energy Outlook 2001*, DOE/EIA-0383(2001) (Washington, DC, December 2000), Table A19; and World Energy Projection System (2001).

2.6.6.1. *Carbon dioxide emissions*

World carbon dioxide emissions in 1990, 1998 and 1999, together with projections to 2020, are given in Table 2.8 for an assumed "high" rate of economic growth. An alternative scenario of "low" economic growth, from the same source, results in figures 2%–5% below the data of Table 2.8.

It is clear from Table 2.8 that carbon dioxide emissions are expected to rise continuously until the year 2020 and probably beyond. As might be expected, the bulk of the emissions originate in the industrialised countries of the OECD group. Corresponding tables in respect of the particular fossil fuels coal, oil and natural gas are given in appropriate chapters below. Because of the amount used, oil is responsible for more carbon emissions than coal, as illustrated in Fig. 2.20. If energy consumption grows at presently projected levels, the annual carbon dioxide emissions will reach 8 billion tonnes in 2010 and 9.8 billion tonnes in 2020. Thus world carbon dioxide emissions would exceed the 1990 levels by 56% in 2010 and would more than double by 2020.

International concern about the levels of carbon dioxide emissions and the possible effects on climate resulted in the Kyoto Protocol agreement in 1998. This agreement calls for quantifiable goals for emission reductions from participating



Sources: **History:** Energy Information Administration (EIA), Office of Energy Markets and End Use, International Statistics Database and *International Energy Annual 1999*, DOE/EIA-0219(99) (Washington, DC, January 2001). **Projections:** EIA, World Energy Projection System (2001).

Fig. 2.20. World carbon dioxide emissions by fuel type, 1970–2020 [5].

countries [11]. As of March 1999, 83 countries had signed the Protocol, indicating their agreement in principle. But ratification and action on the agreement would involve major reductions of energy use and major changes of industrial organisation and employment patterns. In 2001 the USA formally rejected the Protocol and declined to sign because of possible damage to its energy industries and also because of scientific reservations about the global warming levels suggested in the calculations. Everyone is agreed on the need for action but none of the major players have yet (2002) been able to implement it.

2.6.6.2. *Gaseous emissions and the "greenhouse" effect*

Fossil-fuel burning plants emit a variety of flue gases, including oxides of sulphur, oxides of nitrogen, oxides of carbon plus methane and chlorofluorocarbons (CFCs). In addition, a major source of air pollution is from automobile exhausts, which are particularly responsible for carbon monoxide, nitrogen dioxide and hydrocarbons. These automobile pollutants may interact biologically and chemically with those from electricity-generating plants. Carbon monoxide (CO) is a dangerous gas to animals and humans because it is an active oxygen seeker. It readily combines with haemoglobin, which is the oxygen carrier in the bloodstream. A forecast of the anticipated growth of gaseous emissions is shown in Fig. 2.21 [12].

Carcinogens are also present in fossil fuel emissions, particularly those from coal. Various environmental effects such as acid rain are discussed in Chapter 4.

The so-called "greenhouse" effect, applied to the earth's climate, is a scientific theory that was first proposed about 100 years ago but is still the object of some dispute. The earth's gaseous atmosphere permits the easy transmission of incoming ultraviolet, visible and infrared solar radiation that is mostly reflected back from the earth's surface. (Note: A more detailed account of "greenhouse" gas physics is included in Chapter 11 below.) The net radiation effect on the atmosphere is to create a thermal barrier around the earth, resulting in a possible slow increase of the earth's ground temperature. There is uncertainty over the precise rate and ultimate magnitude of any global temperature rise. A 1983 report by the US Environmental Protection Agency (EPA) stated a possible increase of 2°C by the middle of the 21st century and a 5°C increase by 2100. This would result in "a rise in global average sea level and dramatic changes in precipitation and storm levels" [13].

A more recent study involving 28 experts from 12 countries plus 6 modelling teams from the USA studied 40 different emissions scenarios. A consensus view is that global temperatures will increase in the range 1.4°C–5.8°C during the 21st century, with rises in sea levels in the range 8 cm–99 cm [14].

The principal greenhouse gas emissions carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are combined to show results in "equivalent carbon dioxide", in Table 2.9 [15]. The equivalences were obtained using the global warming potentials reported by the Intergovernmental Panel on Climate Change, 1999 [16]. Because some countries did not provide data under certain headings, or did not

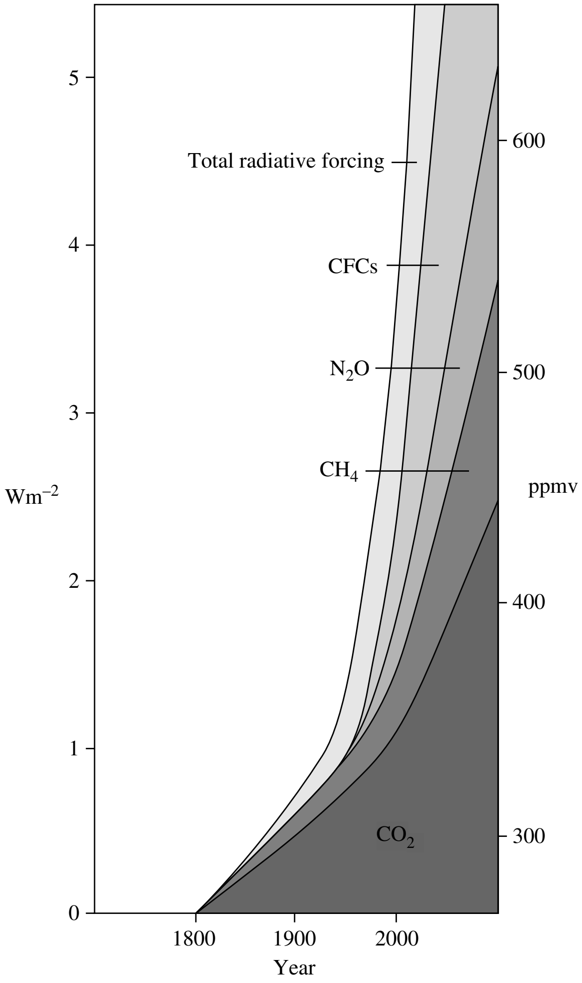


Fig. 2.21. World greenhouse gas emissions [12]. CH_4 = methane; N_2O = nitrogen oxide; CO_2 = carbon dioxide; CFCs = chlorofluorocarbons.

report at all, the information in Table 2.9 should be regarded as partial and subject to revision.

In the column labelled "Forestry and Change of Land Use" of Table 2.9 most of the figures are negative, implying the absorption of greenhouse gases. This is a result of forestation and agricultural planting with the resultant increased digestion of carbon dioxide.

Australia has the world's highest greenhouse gas emissions per person at 26.7 tonnes, which is twice the average level for industrialised countries (13.4 tonnes) and 25% higher than the figure for the USA (21.21 tonnes).

It is seen from Table 2.9 that the six nations with the highest per capita emissions are, in order, Australia, Luxembourg, the USA, Canada, New Zealand and Ukraine.

Table 2.9. Greenhouse gas emission/capita [15, 16] (1995 figures; million tonnes).

Country	Fuel Combustion	Industry	Agriculture	Waste	Forestry And Change of Land Use	Other	Total Emissions	Population	Per Capita Emissions
Australia	291.77	7.45	8.36	16.36	+51.87	27.13	481.94	18.07	26.67
Belgium	112.83	14.27	11.52	4.99	-2.06	1.01	142.56	10.14	14.06
Canada	478.96	36.34	25.04	19.47	0	51.51	611.32	29.62	20.64
Czech. Rep.	130.37	5.22	3.45	3.02	-5.45	8.81	145.42	10.33	14.08
Denmark	58.91	1.31	16.17	1.55	-0.96	1.17	78.14	5.23	14.94
France	365.79	40.79	48.88	19.15	-46.8	24.2	452.06	58.14	7.78
Germany	885.13	50.31	61.52	39.9	-30	24.57	1031.43	81.66	12.63
Greece	84.79	8.33	8.37	2.77	0	1.03	105.29	10.45	10.08
Ireland	33.27	2.58	19.28	2.95	-6.23	0.98	52.83	3.6	14.68
Italy	425.2	29.31	41.84	21.65	-24.51	22.46	515.95	57.3	9.0
Japan	1162.1	68.65	20.65	28.54	-94.62	5.06	1190.38	125.57	9.48
Luxembourg	9.16	0.41	0.51	0.08	-0.3	0.05	9.92	0.41	24.19
Netherlands	183.66	7.61	18.31	9.13	-1.7	5.05	222.06	15.46	14.36
New Zealand	24.95	2.74	44.33	2.77	-13.49	1.39	62.69	3.66	17.13
Norway	29.89	8.52	3.88	6.78	-13.64	2.69	38.12	4.36	8.74
Poland	365.18	13.76	22.87	17.96	-41.95	19.13	396.94	38.59	10.29
Portugal	47.92	4.01	6.33	13.77	-1.15	0.53	71.41	9.92	7.2
Russian Fed.	1607.27	24.37	114.53	41.04	-568	307.2	1526.37	148.2	10.3
Spain	221.62	18.85	37.64	15.3	-28.97	13.45	277.88	39.21	7.09
Sweden	56.29	5.17	4.2	1.28	-30	0.27	37.21	8.83	4.21
Switzerland	40.95	2.71	5.84	2.85	-5.1	0.46	47.72	7.08	6.74
Ukraine	671.17	33.7	50.5	19.68	-51.98	138.06	861.12	51.55	16.7
UK	533.77	28.93	26.19	38.44	+9.95	25.47	662.75	58.61	11.31
USA	5206.4	96.43	268.23	236.44	-428	202.49	5581.99	263.17	21.21

Luxembourg's very high per capita emissions are due to the small population and the presence of a large steel plant. New Zealand has low emissions from energy use, due to the predominance of hydroelectricity, but very high emissions from agriculture due to the large number of sheep!

Some of the larger industrial countries, such as France (7.78), Germany (12.63), Spain (7.1), Italy (9.0) and Japan (9.5), have low per capita emissions due to a combination of energy efficiency, industrial structure and the use of nuclear power (which does not create greenhouse gases) [15].

A major increase of CO_2 emission from earth-bound activities would cause the level of atmospheric CO_2 to build up, possibly increasing the thermal insulation effect. Any additional heat produced by the greenhouse effect would first be absorbed and distributed by the oceans, so introducing a time lag of several decades before the air temperatures increased.

Increasing the level of atmospheric CO_2 would, via any consequent temperature changes, have the effect of redistributing agricultural productivity across the world and possibly lead to mutant changes in plant and animal life. In some regions there could be ecological disaster. It remains conjectural as to whether the danger posed by the greenhouse effect is a reality. The attitude "wait and see" is potentially as dangerous as the threat itself. Due to various positive feedback effects within the earth's complicated climatic cycle, by the time that climatic changes due to excessive CO_2 were detected and attributed they would be irreversible and progressively cumulative.

Nuclear reactors have smaller effects on climate than fossil fuel systems because they do not emit CO_2. Hydroelectric and geothermal sources also do not contribute significantly to greenhouse gases. The manufacture of solar photovoltaic panels is an energy use that might require fossil-fuel-generated electricity but the operation of the panels themselves is benign.

Will the use of fossil fuels be controlled to limit the "greenhouse" danger, by the application of the Kyoto Protocol or otherwise? Will the oil and natural gas run out before their use has irrevocably changed the atmospheric CO_2 levels? Will nature find a way to automatically redress any temperature rise? Is it already too late because the initiating changes are irreversible and are already in place? Have the scientists misread or misinterpreted the data and, in fact, there is no danger?

2.7. Summary — Where Do We Go from Here?

The sociology and politics of energy planning are enormously complicated. Should a particular country have an overall energy policy or is this an unwarranted interference in the freedom of its citizens? Are there overall considerations regarding the welfare of the country, in energy matters, that transcend the rights of individuals? Is energy use and conservation so important as to justify mandated government control?

For the OECD countries the critical near-term factor in energy supplies is the availability of liquid fuels. Modifications of petroleum usage and energy conservation measures of various kinds may delay the final scene but the end point is inevitable. The oil is running out. Energy planning on the scale that is needed involves a lead time of several decades.

For the industrialised and developed countries of the OECD two principal energy problems exist:

Problem 1

A need for continuing sources of gasoline and diesel fuel for motor vehicles and aircraft.

Problem 2

A need for continuing sources of prime fuel for use in the generation of electricity (on the assumption that oil and natural gas will ultimately be unavailable).

2.7.1. *An energy strategy*

Problem 1, concerning oil supply, can be addressed in terms of

- new oilfield discoveries
- enhanced recovery rates of natural crude oil
- development of a synthetic fuels industry
- major social adjustments in the pattern of private motoring
- some alternative form of road transportation (such as the electric car)
- further development of mass transportation systems using electricity-powered rail vehicles

Problem 2, concerning electricity generation, can be addressed simultaneously on both short-term and long-term levels.

In the short term:

- new natural gas field discoveries and enhanced recovery rates
- coal and coal products such as coal-bed methane
- reinstatement and increased use of nuclear fission power, using breeder reactors

In the long term, the future seems to lie with renewable energy sources:

- solar energy
  - photovoltaic conversion
  - solar-thermal systems
  - wind turbine systems
  - ocean thermal currents
  - water wave energy
  - hydropower
  - biomass and photosynthesis
- geothermal energy
- gravitational energy
- tidal energy
- thermonuclear fusion

World energy consumption grew by 2.5% from 1999 to 2000. Consumption in all of the world areas in Fig. 2.2 showed increases.

A recent forecast of future energy demand by the Shell Oil Company is given in Fig. 14.3 of Chapter 14. This puts forward the view that in the next 50 years there will be decreasing use of fossil fuels, especially oil, and increasing use of renewable energy sources.

2.8. Problems and Review Questions

2.1. If the total solar radiation intercepted by the earth has the value equivalent to 1.73×10^{17} J/s, calculate the diametric area if the solar constant is 1377 W/m^2.

2.2. The outward flow of power from the earth's interior proceeds at an estimated rate of 0.063 W/m^2. If the total flow rate is 3.203×10^{13} W, calculate an approximate value for the earth's radius.

2.3. The daily output of energy from the sun is 3×10^{32} J. What fraction of this is intercepted by the earth?

2.4. The solar constant for the planet earth is 1377 W/m. If the effective diametric radius is 6.36×10^6 m, what is the radiation rate?

2.5. Compile a table of data, based on Fig. 2.1, showing the proportions of input solar energy for the earth that are used for (i) direct conversion to heat, (ii) winds, waves, water currents and convection, (iii) the evaporation, precipitation and drainage cycle, (iv) photosynthesis.

2.6. What were the principal reasons for the sudden mass use of fossil fuels in about 1700 AD?

2.7. Use the data of Fig. 2.3 to roughly estimate the number of years of crude oil supply remaining, based on present predictions of use and present reserves for (a) the world, (b) the OECD countries, (c) the former Soviet Union.

2.8. Repeat Problem 2.6 for natural gas supply.

2.9. Repeat Problem 2.6 for coal supply.

2.10. Why does Norway occupy so favourable a position in Fig. 2.8?

2.11. What should be the ambition of a country with regard to its Fig. 2.8 coordinate position?

2.12. Japan has achieved very successful economic performance in spite of poor indigenous energy supplies. What are some of the implications of this for Third World developing countries?

2.13. Why are the agriculture-based economies of Canada, Australia and New Zealand favourably located in Fig. 2.8?

2.14. What are the main reasons why North Americans consume such a high per capita amount of energy?

2.15. In Fig. 2.8 the countries in the bottom left-hand corner, including Brazil, China, India and Indonesia, total 44% of the world population. What are some of the implications of these countries seeking to obtain a "bigger share of the cake"?

2.16. The data of UK primary fuel consumption and production since 1973 are given in Tables 2.5 and 2.6. What do you deduce about the place, in the UK industrial scene, of the coal, gas and oil industries?

2.17. Great Britain is now an oil-based economy with about one human generation period of oil and natural gas remaining. What consequent steps would you advocate as a national policy?

2.18. Which countries of the OECD group supply more than 50% of their energy needs from non-fossil sources?

2.19. What measures would you advocate to reduce the amount of carbon dioxide produced by automobiles?

2.20. Should there be an "emissions tax" to penalise the parts of industry that generate large volumes of greenhouse gases and/or particulates?

2.21. Is there any way in which implementation of the Kyoto agreement can be enforced?

2.22. Use the data of Table 2.9 to list, in order, (a) the six largest energy users, (b) the six largest per capita energy users.

2.23. Why are the agriculture-based economies of countries such as Australia, Ireland and New Zealand such large per capita producers of greenhouse gases?

2.24. Why is Japan, for example, with a large population and highly industrialised economy, such a low per capita contributor to the production of greenhouse gases?

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CHAPTER 3

ELECTRICITY

3.1. Introduction

Electricity is the universally popular form of energy that is always in demand. It is invisible, odourless, available by flicking a switch, easy to measure and meter, and has very wide and varied applications. It continues (2002 AD) to be the most rapidly growing form of energy consumption. When electricity has to be manufactured from some source of fossil fuel it can be regarded as a secondary form of energy. Electricity generated from nuclear or hydro sources can be regarded as primary energy.

3.2. Some Basic Electrical Relationships

3.2.1. *Voltage, current and power*

The potential energy of an electricity supply system is measured in terms of electrical "pressure" or voltage, named after the Italian scientist Alessandro Volta. The unit of potential difference between two points in a circuit is the volt (V), which represents an energy of one joule per coulomb of charge. Electricity supplies for domestic consumers are usually rated at 240 V in the UK and 120 V in the USA. Silicon solar cells are rated at about 0.5 V, small dry batteries are rated at 1.5 V, while car batteries are usually 12 V. For the transmission of electricity by overland line or underground cable, the transmission voltages range up to several hundred thousand volts (i.e. several hundred kV).

The application of an electrical voltage to a circuit results in the flow of electric current measured in amperes (A), named after the French scientist Andre Marie Ampère. Small values of current are measured in microamperes (μA) or milliamperes (mA). Domestic appliances such as washing machines operate with currents of the order 3 A–5 A. Large industrial machines or processes take currents of tens (or even hundreds) of amperes. A lightning stroke is an electrical discharge that might involve millions of amperes, for its few seconds of duration. It is the current rating of an electrical load that determines the size of connecting wires or conductors.

Electrical current flow in a circuit is opposed by the circuit impedance. With a direct current (DC) supply the circuit impedance is entirely resistive and the load is a resistance R measured in ohms, after the German scientist Georg Simon Ohm. The relationship between voltage, current and resistance (or impedance) is called Ohm's Law.

$$R = \frac{V}{I} \tag{3.1}$$

When V is in volts and I is the current in amperes, then resistance R has the unit of ohms.

The time rate of energy dissipation in a DC circuit, or circuit power rating, is given by

$$P = VI \tag{3.2}$$

When V is in volts and I is in amperes, the unit of power is the watt (W), named after the Scottish engineer James Watt. One watt is an energy dissipation rate of one joule per second (J/s).

Equations (3.1) and (3.2) can be combined to give the power in terms of load resistance R:

$$P = I^2R = \frac{V^2}{R} \tag{3.3}$$

Most electricity supply systems generate alternating current (AC) rather than direct current (DC), for economic reasons. In an AC system the voltages and currents vary sinusoidally (usually) in magnitude and direction at a time rate defined as the frequency of operation. Frequency is measured in units of cycles per second or hertz (Hz), named after the German scientist Heinrich Hertz. In the USA the domestic and most industrial electricity supplies operate at 60 Hz, whereas in the UK the preferred frequency is 50 Hz. Radio transmission usually operates at frequencies of hundreds of thousands of Hz (i.e. several hundred kHz). Television picture signals are of the order hundreds of millions of Hz (i.e. hundreds of MHz). The visible spectrum of solar radiation is approximately of frequency 6×10^{14} Hz.

Because of the time variation of the voltages and currents, the circuit properties of AC quantities that are usually used are the root mean square (rms) values. The rms value of an AC variable is sometimes called the effective value because it is effectively equal to the DC value that would dissipate the same power. When a circuit is rated at (say) 240 V it means that the applied voltage has an rms value of 240 V. Most electricity supply systems operate with constant rms voltage.

With an alternating current (AC) supply the load may be resistive, as with electric lamp and heating loads. For industrial loads, however, where the load is often due to three-phase AC induction motors, the load is partly inductive in nature. The combination of resistance R and inductance L effects is conjoined in the AC impedance Z, which depends on the (usually constant) frequency of the AC supply.

For AC circuits Eq. (3.1) is modified to

$$Z = \frac{V}{I} \tag{3.4}$$

Equation (3.3) is still valid for the resistance components in an AC circuit provided that I and V are the rms values.

In an AC circuit the power dissipation in watts is no longer generally described by (3.2). Because of time-phase effects caused by magnetic field and electric field properties, the power is reduced and is now given by

$$P = VI\cos\Phi \tag{3.5}$$

In (3.5) the angle Φ depends on the amount of inductance or capacitance in the circuit load. With purely resistive loads $\Phi = 0°$, $\cos\Phi = 1$, and (3.5) becomes equal to (3.2). The property $\cos\Phi$ in (3.5) is often referred to as the power factor (PF). It is a constant aim of electrical engineers to operate circuits and systems at the highest possible value of power factor. When the PF $= 1$, its highest possible value, it means that the specified load power P is being supplied using the minimum possible value of supply current I and this is the most economic condition of operation. In some electrical engineering books the term "power factor" is alternatively designated as "energy efficiency".

The most effective and economic form of electricity generation and distribution is to use three-phase systems. With a three-phase AC generator supplying a balanced load it is possible to supply three separate one-phase loads using four (sometimes three) conductors. With three-phase loads Eqs. (3.1)–(3.5) remain valid but refer to per phase quantities.

One of the great advantages of using AC supply systems is that the voltage levels can be easily changed using electrical transformers. In order to use small area conductors, thereby saving on the cost and weight of copper, a transmission circuit is made to operate with low values of current. But with low current it is necessary to use very high transmission voltages in order to transmit a lot of power, as implied in (3.2) and (3.5). Figure 3.1 shows a typical arrangement of three-phase, high-voltage towers or pylons, rated at several hundred kV [1]. At the receiving end of the transmission lines the high voltages are transformed to much lower values for distribution and use, while the low transmission line currents correspondingly increase. The large sizes of apparatus needed are illustrated by the high-voltage transformer and switchgear of Fig. 3.2 [2].

The efficiency ($\boldsymbol{\eta}$) of operation of an electrical circuit or system is defined as the ratio of the output power to the input power:

$$\boldsymbol{\eta} = \frac{P_{\text{out}}}{P_{\text{in}}} \tag{3.6}$$

For a resistive circuit such as an electric heater, the efficiency is high, probably well over 90%. With an electric motor load the full-load efficiencies vary from about 60% for small motors to over 90% for large motors.

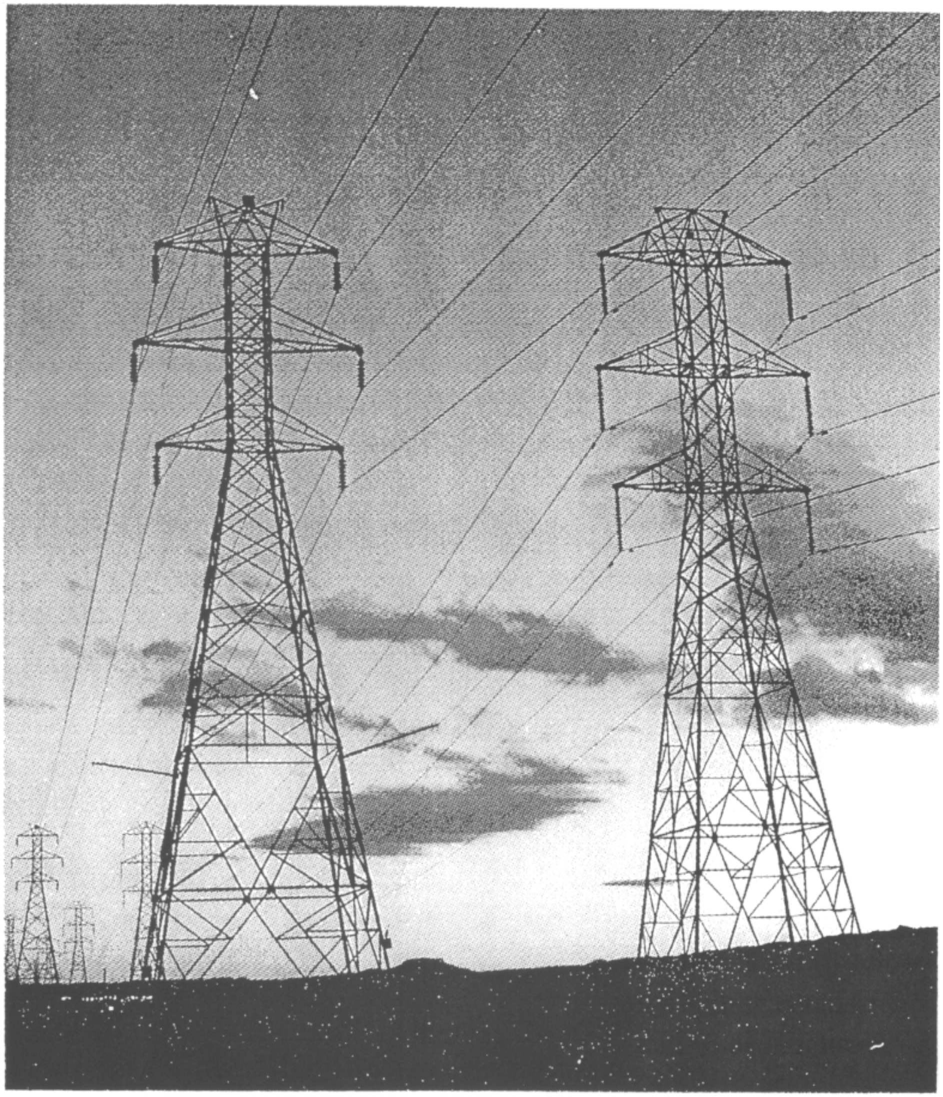


Fig. 3.1. Three-phase, high-voltage transmission line [1].

It should be noted that efficiency is not the same as power factor (i.e. energy efficiency). For a full assessment of an AC circuit performance both the efficiency and the power factor need to be considered. The total tariff (i.e. electricity bill) paid by an industrial consumer depends not only on the kilowatt hours of electrical energy consumed but also on the maximum demand figure and the operating power factor.

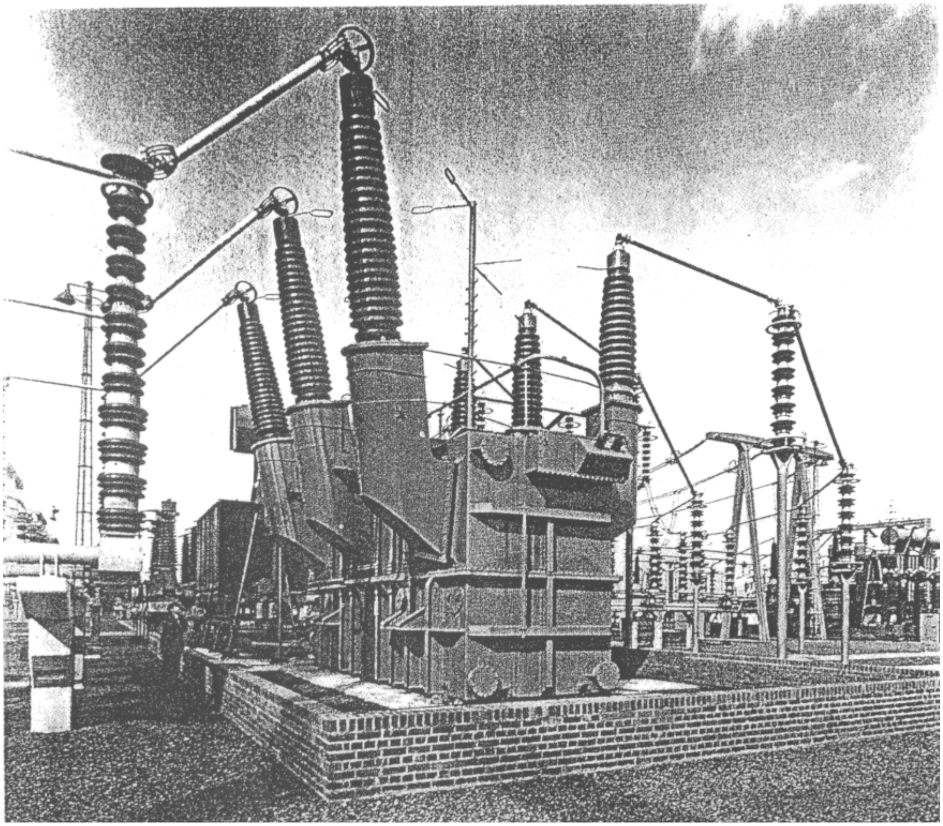


Fig. 3.2. High-voltage transformer and switchgear (courtesy of *Energy*, Marshall *et al.* Cavendish Books Ltd, London, 1978).

3.2.2. *Worked examples on electrical circuits*

Example 3.1

A 120 V, 60 Hz single-phase electric supply is connected to a load of resistance 24 ohms. Calculate the current and the power dissipation.

From (3.1),

$$I = \frac{V}{R} = \frac{120}{24} = 5 \text{ A}$$

From (3.3),

$$P = I^2 R = (5)^2 \cdot 24 = 600 \text{ W}$$

Example 3.2

For a single-phase 240 V, 50 Hz supply the instrument readings with a certain electric motor load are $I = 12$ A, $P = 1500$ W. Calculate the input impedance of the motor and its operating power factor.

From (3.4),

$$Z = \frac{V}{I} = \frac{240}{12} = 20 \text{ ohms}$$

From (3.5),

$$\begin{aligned} PF = \cos\Phi &= \frac{P}{VI} \\ &= \frac{1500}{240 \times 12} = 0.52 \end{aligned}$$

Note that this is a low (poor) value of PF and represents a poor form of utilisation.

Example 3.3

An AC electric motor has a nameplate rating of 1 kW. When it delivers its rated load from a 240 V, 50 Hz supply the input power is 1500 W. What is the motor efficiency?

A motor nameplate rating represents its output power at full load. Therefore,

$$P_{\text{out}} = 1000 \text{ W}$$

$$P_{\text{in}} = 1500 \text{ W}$$

From (3.6) the efficiency is

$$\begin{aligned} \eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{1000}{1500} &= 0.667 \\ &= 66.7\% \end{aligned}$$

3.3. The Generation of Electricity

An electricity generator is a machine for converting mechanical energy into electrical energy. When coal, natural gas, oil or nuclear fuels are used the fuel is first converted into heat energy and then into mechanical energy by a turbine. The mechanical energy is usually rotational in form and the so-called prime mover that rotates the generator shaft is usually a steam turbine, diesel engine or gas turbine. Generation plants that operate via a heat–work process are called thermal stations to distinguish them from more direct systems such as wind turbines and water turbines. An illustration showing the essential features of a coal-fired electricity generation system is given as Fig. 1.5 in Chapter 1.

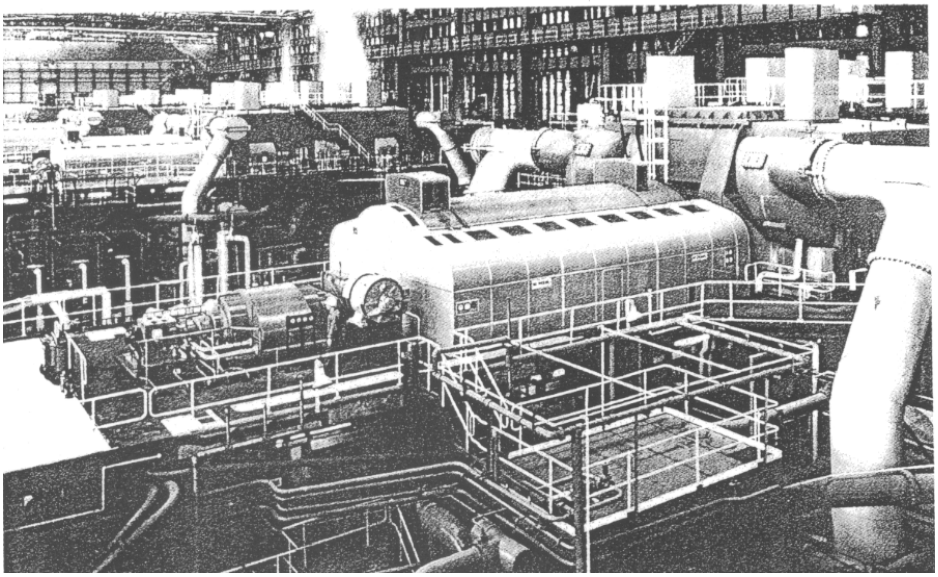


Fig. 3.3. Four 500 MW turbo-alternators (Ref. *Energy*, Marshall *et al.* Cavendish Books Ltd, London, 1978).

Electrical generators work on the principle of electromagnetic induction, discovered by the English scientist Michael Faraday in the early 1800s. An arrangement of coils on the rotating part (rotor) causes a magnetic field to rotate at the shaft speed. This induces electromotive forces (voltages) in the conductors of the armature coils mounted on the machine frame (stator). Both the magnitudes and frequencies of the induced or generated voltages are proportional to the speed of shaft rotation. Generator and transformers are usually rated in terms of voltamperes (volts × amps at full load) rather than in terms of watts, to accommodate power factor effects. The largest individual generators, often called turbo-alternators, are rated at about 600 MW. The size of comparable machines is illustrated in Fig. 3.3. Generators as small as 1 kVA rating are used in some applications. The 400 Hz generators used on board large jet airliners, driven by the high-speed jet engines, are rated at about 40 kVA.

3.4. The Siting of Electrical Power Plants

The precise choice of location for an electric power station or power plant involves several technical and non-technical considerations [2]:

(i) fuel supply
(ii) water supply
(iii) land elevation
(iv) road and rail access

(v) height of the structures
(vi) disposal of waste products
(vii) proximity to populated areas
(viii) environmental implications

3.4.1. *Fuel supply*

There must be proximity to economic sources of fuel. For coal-fired stations there must be rail access. For oil-fired stations the site must be within pipeline range of a refinery or have access to a deep-water anchorage. For nuclear stations the source and distance of the fuel supplies is not a critical issue.

3.4.2. *Water supply*

There must be an adequate and secure supply of cold water to cool the condensed (liquefied) steam of thermal electrical power plants. This is illustrated in Fig. 1.5 by the closed water pipe that transfers water to and from the river to the turbine-generator house. A 2000 MW plant requires up to 60 cubic metres/second (m^3/s). The piping of adequate water supply over large distances would be prohibitively expensive, so power plants are often built on the sea coast or alongside rivers or lakes. When the local water supply has an insufficient flow rate, cooling towers must be used. These tend to be large, unsightly, concrete and steel structures, Fig. 3.4, with their effluent steam being visible for several miles around. At a 2000 MW station the cooling towers evaporate water at the rate of 50,000 cubic metres per day. This is about one hundredth of the natural water content of the ambient air passing over on an average day. The cooling towers themselves require, during their periods of operation, about 2 m^3/s of water to make good the evaporation losses and to prevent the build-up of dissolved impurities in the cooling water.

3.4.3. *Land elevation*

A power station requires a fairly level area of ground of the range 120–370 acres. It must be sited above the flood-water level but not so far above that the necessary pumping of cooling water becomes too expensive. Power plant buildings and equipment are large and heavy, requiring ground areas that have solid foundations of rock.

3.4.4. *Road and rail access*

The construction phase of a power plant requires a heavy flow of site traffic, which in turn requires access to the existing road network. Rail access is necessary to transport the fuel for coal-fired stations.

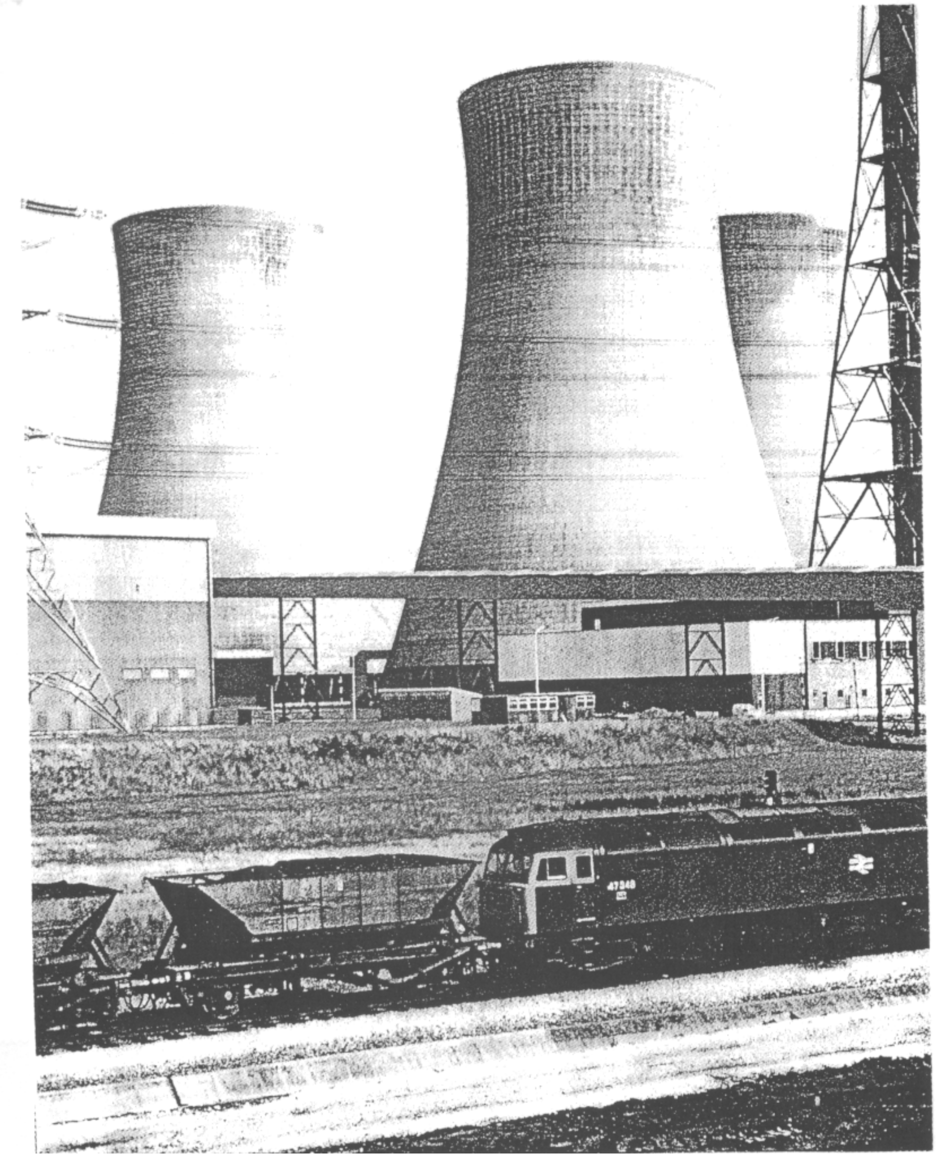


Fig. 3.4. Cooling towers.

3.4.5. *Height of the structures*

Chimneys and cooling towers are tall structures, sometimes being more than 100 m high, to elevate the plumes of smoke and steam. The heights of the structures must comply with local environmental planning rules and also with airport safety regulations if the site is in the vicinity of an airport.

3.4.6. *Disposal of waste products*

For coal-fired stations it is necessary to have nearby facilities for dumping large quantities of pulverised fuel ash. This can subsequently be grassed and landscaped. The disposal of waste from nuclear stations is a special case that is dealt with in Chapter 8.

3.4.7. *Proximity to populated areas*

In the UK it is necessary to site nuclear stations remotely from large population areas for legal reasons. A correspondingly remote location of fossil-fuel burning stations is quite impossible in a small and densely populated country like Britain.

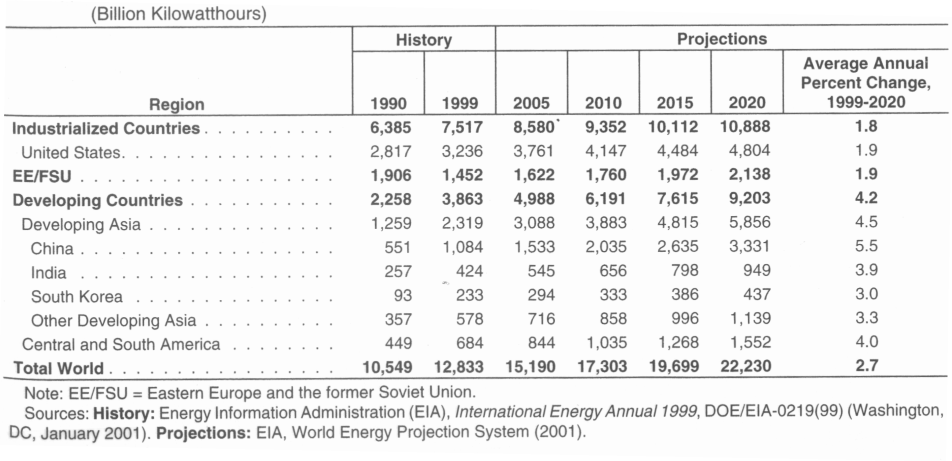
3.4.8. *Environmental implications*

The environmental implications of burning coal, oil, natural gas and nuclear fuels to generate electricity are discussed in Chapters 4, 5, 6 and 8, respectively. For example, electricity generation accounts for about one-third of total carbon dioxide emissions in Western Europe and North America. Carbon dioxide is believed to be the main cause of global warming due to human activity [3].

3.5. World Electricity Consumption

The most recent data available on world electricity consumption refers to 2000 with onward projections, and is given in Table 3.1 [4]. The four biggest consumers were the USA, the former Soviet Union, Japan and China. These four countries are also the largest consumers of primary energy, shown in Table 2.2 of Chapter 2. As with

Table 3.1. World net electricity consumption by region, 1990–2020 [4].



(Billion Kilowatthours)

	History		Projections				
Region	1990	1999	2005	2010	2015	2020	Average Annual Percent Change, 1999-2020
Industrialized Countries	**6,385**	**7,517**	**8,580**	**9,352**	**10,112**	**10,888**	**1.8**
United States	2,817	3,236	3,761	4,147	4,484	4,804	1.9
EE/FSU	**1,906**	**1,452**	**1,622**	**1,760**	**1,972**	**2,138**	**1.9**
Developing Countries	**2,258**	**3,863**	**4,988**	**6,191**	**7,615**	**9,203**	**4.2**
Developing Asia	1,259	2,319	3,088	3,883	4,815	5,856	4.5
China	551	1,084	1,533	2,035	2,635	3,331	5.5
India	257	424	545	656	798	949	3.9
South Korea	93	233	294	333	386	437	3.0
Other Developing Asia	357	578	716	858	996	1,139	3.3
Central and South America	449	684	844	1,035	1,268	1,552	4.0
Total World	**10,549**	**12,833**	**15,190**	**17,303**	**19,699**	**22,230**	**2.7**

Note: EE/FSU = Eastern Europe and the former Soviet Union.

Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 1999*, DOE/EIA-0219(99) (Washington, DC, January 2001). **Projections:** EIA, World Energy Projection System (2001).

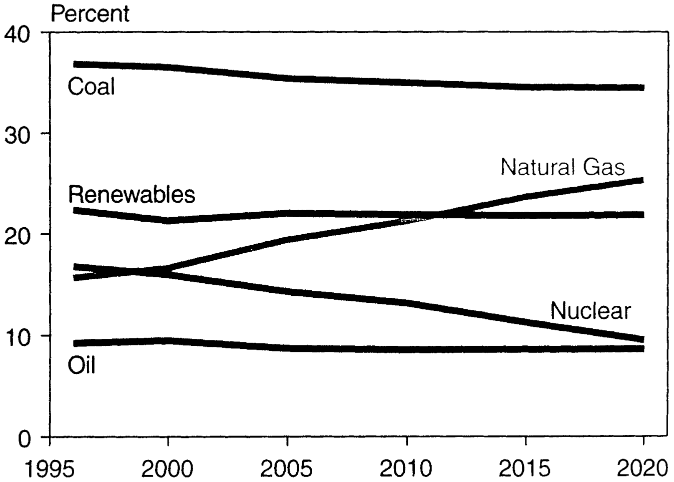
Table 3.2. World energy consumption for electricity generation by region and fuel, 1995–2020 [4].

(Quadrillion Btu)

Region and Fuel	History		Projections			
	1995	1999	2005	2010	2015	2020
Industrialized	**77.1**	**83.8**	**91.6**	**97.2**	**103.5**	**108.0**
Oil	5.7	6.5	5.4	5.3	5.5	5.9
Natural Gas	9.7	11.6	15.6	18.3	23.1	27.4
Coal	27.7	29.5	32.1	33.4	34.0	34.3
Nuclear	19.4	20.6	20.9	20.9	20.5	19.1
Renewables	14.7	15.6	17.5	19.4	20.4	21.3
EE/FSU	**26.4**	**23.8**	**25.9**	**27.0**	**28.9**	**30.8**
Oil	2.8	2.4	3.1	3.5	4.2	4.7
Natural Gas	10.6	10.3	11.1	12.3	14.4	15.9
Coal	7.4	5.4	5.4	4.5	3.3	2.8
Nuclear	2.5	2.7	3.2	3.1	3.1	2.8
Renewables	3.1	3.0	3.2	3.5	4.0	4.5
Developing	**38.1**	**40.9**	**52.3**	**63.1**	**75.0**	**86.6**
Oil	5.1	5.7	6.9	8.3	10.0	12.0
Natural Gas	4.8	6.0	8.4	11.0	13.6	16.4
Coal	16.8	15.8	20.4	24.7	29.2	32.6
Nuclear	1.4	1.9	2.6	3.4	4.1	5.1
Renewables	10.1	11.5	14.1	15.8	18.2	20.5
Total World	**141.7**	**148.4**	**169.8**	**187.3**	**207.4**	**225.4**
Oil	13.6	14.6	15.4	17.0	19.7	22.5
Natural Gas	25.1	27.9	35.2	41.7	51.0	59.7
Coal	51.9	50.7	57.8	62.5	66.5	69.7
Nuclear	23.3	25.3	26.7	27.4	27.7	27.1
Renewables	27.9	30.0	34.8	38.7	42.5	46.4

Note: EE/FSU = Eastern Europe and the former Soviet Union.

Sources: **History:** Derived from Energy Information Administration (EIA), *International Energy Annual 1999*, DOE/EIA-0219(99) (Washington, DC, January 2001). **Projections:** EIA, World Energy Projection System (2001).



Sources: **1996:** Derived from Energy Information Administration (EIA), *International Energy Annual 1996*, DOE/EIA-0219(96) (Washington, DC, February 1998). **Projections:** EIA, World Energy Projection System (1999).

Fig. 3.5. Fuel shares of world electricity generation, 1996–2020 [5].

primary energy consumption, the countries of North America and Western Europe account for about one-half the total world consumption of electricity. An estimated regional breakdown of the 2000 AD world electricity consumption in terms of the prime fuel used is shown in Table 3.2 [4]. Coal is, by far, the biggest prime fuel source for electricity generation in both OECD and non-OECD regions. For the total world electricity generation in 2000, coal fuelled almost as much as oil, natural gas and nuclear fuels combined, as illustrated in Fig. 3.5.

Electricity generation per capita for certain countries is shown in Fig. 3.6 [5]. As for the total per capita fuel consumption, Fig. 2.8, the USA uses about twice the amount used in Japan and Western Europe. The low quantities of electricity used in China, India and Indonesia also reflect their lowly locations on the GDP/Energy graph of Fig. 2.8 in the previous chapter.

All the projections of future world electricity consumption indicate continual growth. The rates of growth may vary in value between different predictions but all agree on the feature of continuing upward demand. The projection of future electricity demand to the year 2020, Table 3.2, indicates that in 20-plus-year period from 1996, world demand will increase by more than 50%. Coal and oil use for electricity generation will increase by about 40–50% in the period, with natural gas uses more than doubling. In the same period the world use of nuclear power is expected to drop sharply in the forecast, to 10% in 2020 from 17% in 1996. Nuclear power has lost its lustre largely as a result of past cost overruns in building nuclear facilities, the high costs of decommissioning and spent fuel retirement, and

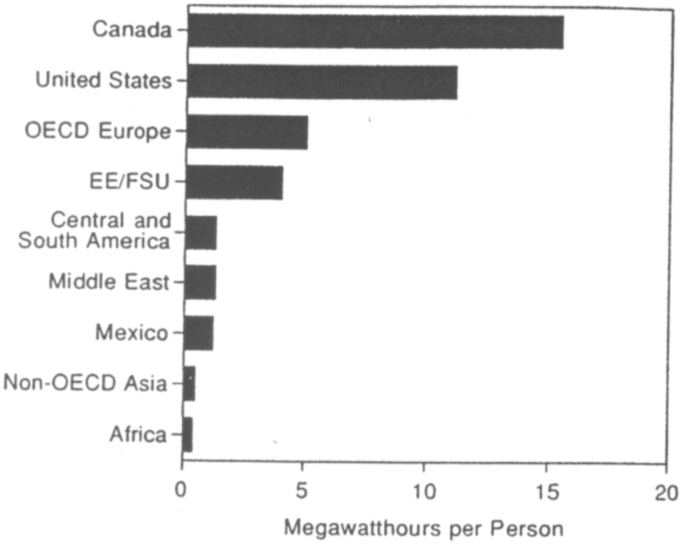


Fig. 3.6. Electricity consumption per capita by region, 1993 [5]. (EE/FSU = Eastern Europe/former Soviet Union.)

growing environmental concerns. Both Sweden and Germany are committed to gradual phase-outs of nuclear power, and other industrialised nations are expected to reduce their nuclear reliance. Only France and Japan are expected to continue to rely on nuclear power to the extent that they have in the past [4].

3.6. UK Electricity

3.6.1. *Consumption and supply*

In the UK the daily variation of electricity demand retains the same form year-by-year. Typical characteristics are given in Fig. 3.7. The weekday load greatly exceeds the Sunday load because of the industrial demand.

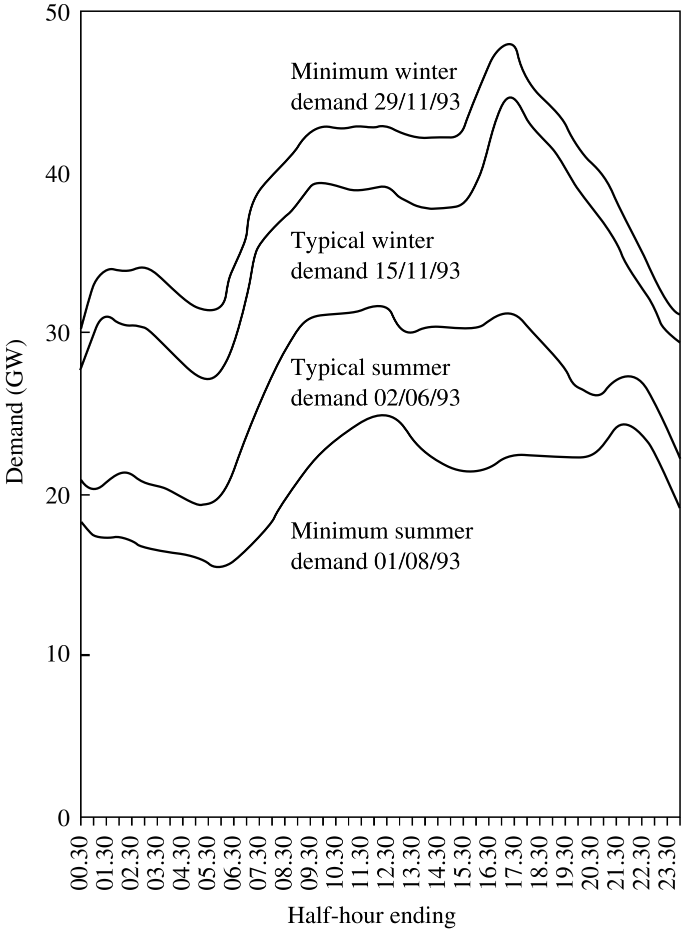


Fig. 3.7. UK daily electricity demand, 1993.

On a typical day the big load demand starts between 7 am and 9 am and lasts until 5 pm to 6 pm. A typical winter load is about 30% higher than the corresponding summer load (Fig. 3.7). It is a feature of electricity supply systems that they must be capable of supplying the maximum demand even if, for a lot of the time, the expensive generation equipment is underused or is completely idle.

Table 3.3. Fuel sources of electricity generation in the UK, 1980–2000 [6].

TWh

	1980	1990	1998	1999	2000
Coal	190.0	208.0	117.0	101.2	114.6
Oil	33.9	21.3	5.9	5.3	5.1
Gas	1.6	1.6	116.3	139.8	143.7
Nuclear	32.3	58.7	90.6	87.7	78.3
Hydro	7.3	7.9	5.1	5.3	5.1
Other fuels			7.8	8.6	8.3
Net imports	—	11.9	12.5	14.2	14.2
Total	265.1	309.4	355.2	362.1	369.3

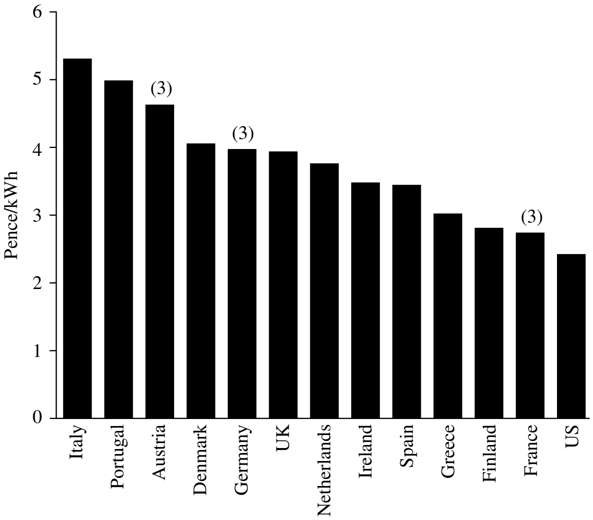


Fig. 3.8. Industrial electricity prices within the EU and G7 countries in 1999: converted to UK pence per kWh [7].

Notes: Prices including taxes where not refunded.
(1) Converted using average 1999 exchange rates.
(2) Data not available for Sweden, Belgium, Japan, Canada and Luxembourg.
(3) 1998 figures.
(4) Figures for Japan in 1997 suggest a price of around 8 pence per kWh.

Source: Derived from IEA data

The demand for electrical power rises each year in the UK. Information concerning the various fuels used for electricity generation is given in Table 3.3 [6].

The mix of fuels used to generate electricity in the UK continues to evolve. In 1999 natural gas supplied more electricity than coal for the first time. Coal's share of the market fell from two thirds in 1980 to under one third in 2000. Nuclear's share peaked at 26% in 1997 but in 2000 slipped back to under a quarter [6].

The natural gas share has risen continuously and in 2000 was 143.7/369.3 or 39%. Renewable energy electricity accounted for 2.8% of the electricity generated in the UK in the year 2000.

In the UK the consumption of electricity is shared almost equally between the industry, domestic and services sectors. Consumption grew by 19% and 29.5% respectively, in the domestic and services sectors, in the ten years to 2000. Industrial consumption also grew to its highest level ever of 114.7 TWh in 2000 [6].

The average domestic demand is about 0.5 kW per household, with a maximum demand in the range 5–10 kW. The 1999 price of electrical energy in the UK is included in Figs. 3.8 and 3.9, for the industrial and domestic sectors, respectively [7]. In these figures the term EU refers to the European Union countries and the term G7 refers to the group of wealthy industrial countries listed in Table 2.1 of Chapter 2. All of the European countries levy some degree of taxation on the price of domestic electricity. In 1999 domestic electricity was most expensive in Denmark, Fig. 3.9, where more than one half of the price was due to taxation.

3.6.2. *Organisation of the UK electricity supply industry in 2001*

The UK has 70 million kilowatts of installed electric capacity, about 79% of which is thermal, 19% nuclear and 1% hydropower. Thermal production is shifting away from heavy reliance on coal toward more environmentally friendly natural gas. The country generated 343 billion kilowatt hours (bkWh) of electricity in 1998, making it the third-largest electricity market in Europe (behind Germany and France).

Electricity privatisation began in the early 1990s, and the final phase of transition ended in May 1999. Initially, all non-nuclear state-owned power stations were privatised and four major generating companies — PowerGen and National Power in England and Wales, and Scottish Power and Hydro-Electric in Scotland — were formed to operate the stations. The grid distribution system in England and Wales became the property of the National Grid Company. Regional electricity boards were privatised as separate distribution companies.

The number of electric generation companies in the UK has increased to 27 as a result of the liberalisation process, according to the UK Department of Trade and Industry. The country's new electricity trading arrangements (NETA) started on November 21, 2000. The introduction of NETA is expected to lead to a more than 10% drop in UK wholesale electricity prices as competition increases. Large industrial buyers have urged the government to reform the existing market, known as the pool, claiming generators have manipulated the system to maintain higher

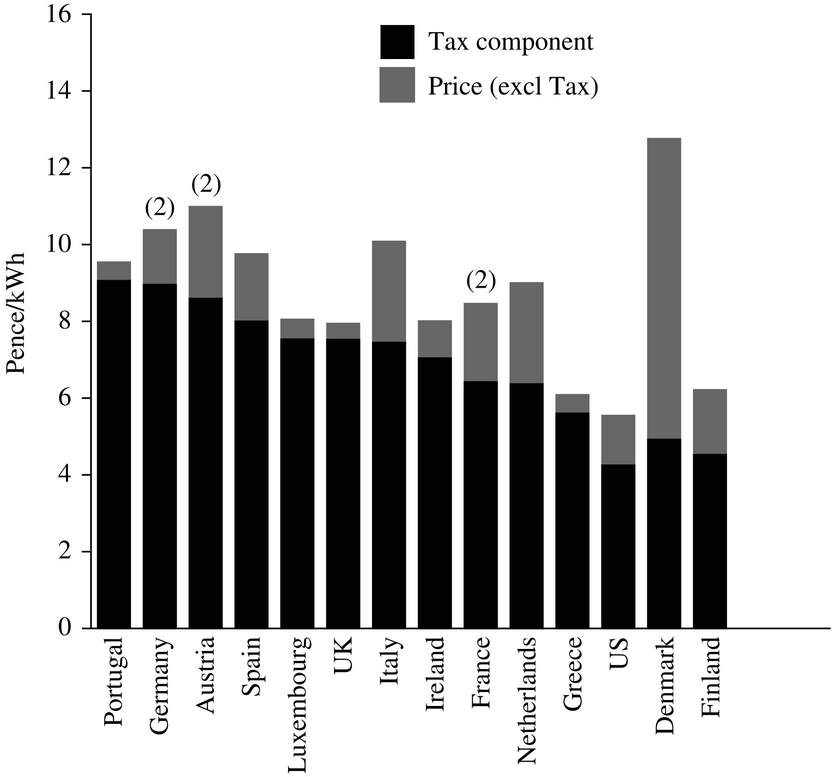


Fig. 3.9. Domestic electricity prices within the EU and G7 in 1999: converted to UK pence per kWh[1,3,4] [7].

Notes: Tax component represents all taxes levied where not refunded.
(1) Converted using average 1999 exchange rates.
(2) 1998 figures.
(3) Data not yet available for Belgium, Sweden or Japan.
(4) Figures for Japan in 1997 suggest a price of around 22 pence per kWh.

Source: Derived from IEA data

prices. Currently, generation companies sell electricity into the pool, organised by National Grid, and distribution companies buy electricity from the pool. Customers buy electricity from the distribution company.

Nuclear power stations were not privatised simultaneously with non-nuclear stations. In 1995, the government announced that it would privatise its more modern nuclear stations while retaining ownership of older stations. In 1996, the more modern stations were privatised and British Energy became the holding company of Nuclear Electric and Scottish Nuclear, which merged in 1998 to form British Energy Generation, the nation's largest private nuclear generator.

Northern Ireland, part of the UK but not part of Great Britain, is served by Northern Ireland Electricity, one of the largest companies in Northern Ireland and part of the Viridian Group. Northern Ireland has a separate electricity and gas regulatory body, Ofreg [8].

3.7. US Electricity Consumption and Production

The fuel sources used for electricity generation in the USA are given in Table 3.4 for the period 1990–2000. The same data is illustrated in the bar chart of Fig. 3.10. Electricity consumption is projected to increase at an average rate of 1.2% per year — one of the smallest increases expected among the industrial economies. Demand growth in the USA has slowed considerably since the 1960s, when electricity consumption was rising at a rate of 7% per year. The saturation of households with electronic appliances and efficiency improvements in such appliances over time are responsible for the slower growth in total electricity consumption.

Coal's share of the US electricity fuels market is expected to hold steady at roughly 50%, Fig. 3.10.

In the USA nuclear power provided 20% of the total electricity production in the late 1990s. There has been a wide expectation that this nuclear share will reduce to about 8% by the year 2020. However, a major review of US nuclear policy is now (2002) under way that leaves the nuclear option open.

Natural gas is expected to gain an increasing share of US electricity production, Table 3.4.

Canada is expected to reduce its dependence on nuclear power over the coming years. Nuclear power, which accounted for 17% of Canada's total electricity generation in 1996, is expected to provide only 7% of total supply in 2020. In all likelihood, Canada may reduce its dependence on nuclear power even more dramatically. The Canadian province of Ontario is currently (2002) re-evaluating the safety of its nuclear power industry. In late 1997 and early 1998, Ontario Hydro shut down seven of its older power plants, or 17% (4300 megawatts) of its operating capacity. At present, it remains uncertain whether the plants will be brought back on line sometime after 2000 as was intended.

Table 3.4. Fuel sources of electricity generation in the USA [9].

Billion kilowatt-hours	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	**2000**	Change 2000 over 1999	2000 share of total
From:													
Oil	124.0	119.0	99.4	112.4	105.5	75.3	81.7	93.0	126.9	123.6	**108.9**	–11.8%	2.9%
Natural gas	378.3	392.6	418.3	428.4	465.9	498.5	455.8	485.4	540.6	556.6	**595.8**	7.0%	15.7%
Coal	1590.3	1589.9	1621.1	1690.0	1691.7	1710.2	1795.7	1844.1	1873.9	1884.3	**1964.6**	4.3%	51.8%
Nuclear	577.0	612.6	618.8	610.4	640.5	673.4	674.7	628.6	673.7	728.3	**753.9**	3.5%	19.9%
Hydroelectric	289.5	285.0	248.9	276.5	256.8	308.3	344.4	354.9	318.9	313.2	**269.0**	–14.1%	7.1%
Others	65.7	72.2	76.8	79.3	93.4	92.2	94.7	88.1	83.8	100.2	**99.7**	–0.5%	2.6%
TOTAL USA	**3024.9**	**3071.3**	**3083.4**	**3196.9**	**3253.8**	**3357.8**	**3447.0**	**3494.2**	**3617.9**	**3706.1**	**3791.9**	**2.3%**	**100.0%**

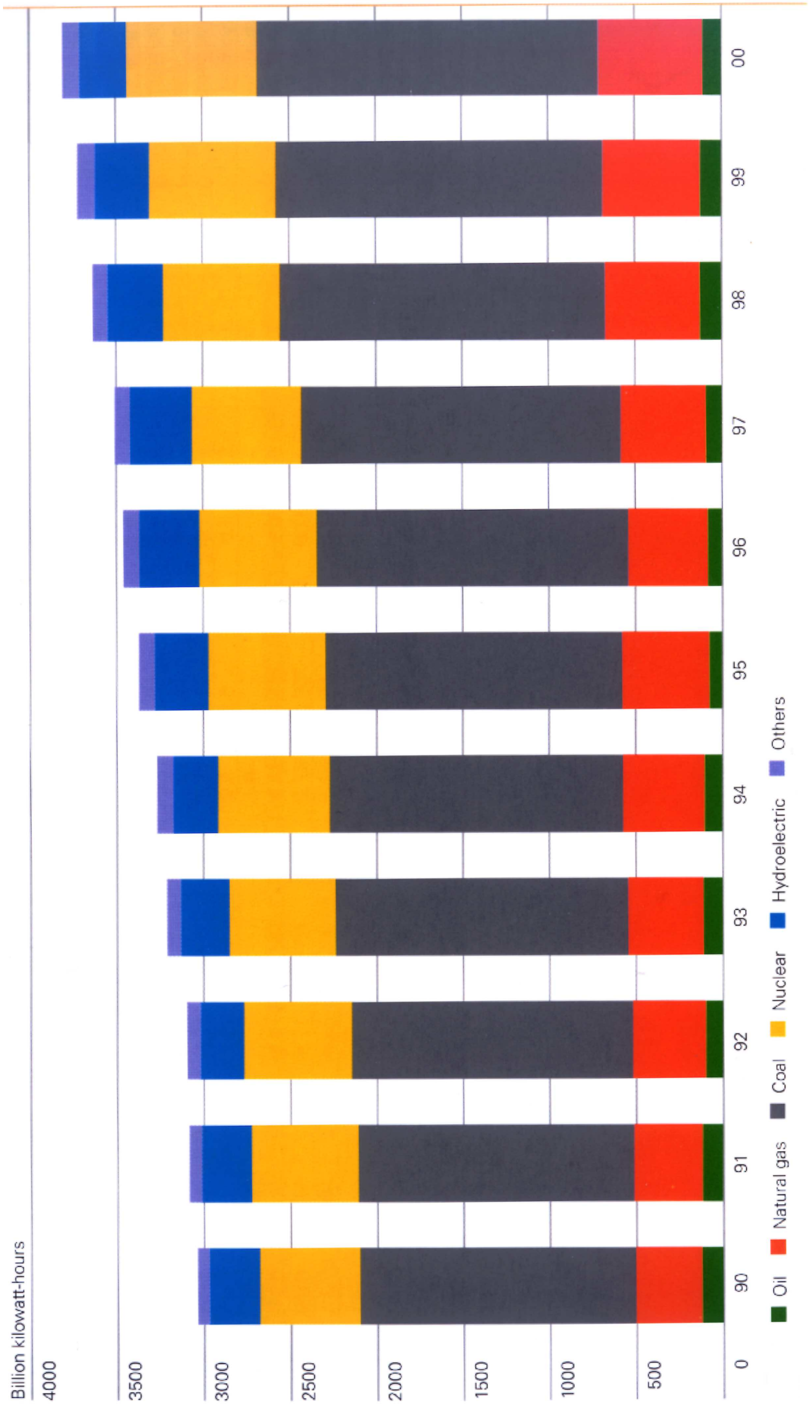


Fig. 3.10. Fuel shares of electricity generation in the USA, 1990–2000 [9].

Historically, the USA has been a net importer of electricity, primarily from Canada. If the Ontario plants are not reopened, the net flow of electricity across the US-Canadian border could be reversed. Natural gas is expected, in large measure, to make up for Canada's reduced reliance on nuclear power and hydroelectricity.

It is noteworthy from Figs. 3.8 and 3.9 that the US price of electricity in 1999 was lower than that in any of the EU or other G7 countries, both for the domestic and industrial sectors. For example, a state-of-the-art combined-cycle plant, in which heat is recovered from the gas cycle to drive a second steam cycle, generally can produce wholesale electricity at the low price of US$0.04/kWh [10].

3.8. Combined Heat and Power (CHP)

A Combined Heat and Power Plant (CHP) is an installation where there is simultaneous generation of usable heat and power (usually electricity) in a single process. High temperature heat from fuel combustion is used to generate electricity while lower temperature exhaust heat can be used for industrial process heat, district heating and space heating. Diagrammatic forms of the CHP process are shown in Fig. 3.11.

In conventional electricity generation, by the use of steam turbines, only 30–35% of the energy originally available in fuel is converted to electricity. The remainder

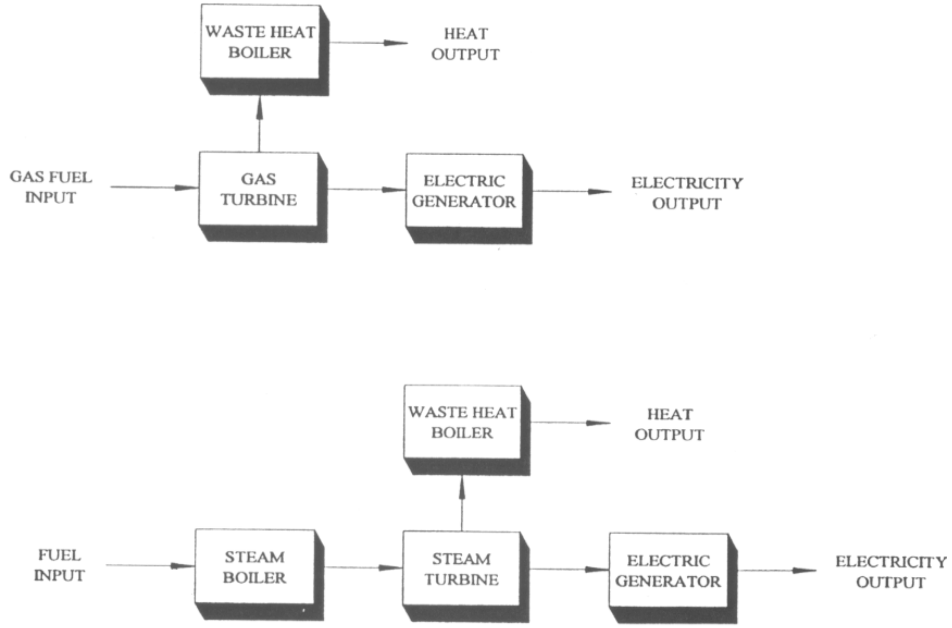

WASTE HEAT BOILER
HEAT OUTPUT
GAS FUEL INPUT
GAS TURBINE
ELECTRIC GENERATOR
ELECTRICITY OUTPUT
WASTE HEAT BOILER
HEAT OUTPUT
FUEL INPUT
STEAM BOILER
STEAM TURBINE
ELECTRIC GENERATOR
ELECTRICITY OUTPUT

Fig. 3.11. Forms of the CHP process.

is converted to hot exhaust gases or to hot water derived from cooling the turbine condensers [11]. If this waste heat can be used, thus saving on other forms of heating, a large gain of overall efficiency can be realised. About 40% of industrial energy is used to produce low-pressure process steam. In the USA and the continental European Community countries, CHP is sometimes referred to as "total energy" or as "cogeneration" [12, 13].

There are five principal types of CHP systems [13]:

(a) Back pressure steam turbine systems, in which high pressure steam is generated in a boiler and wholly or partly used in a steam turbine–generator system. Lower pressure exhaust steam can be extracted at an appropriate site pressure. It is possible to extract some proportion of the steam used by the turbine at an intermediate pressure, giving rise to the name pass-out/back pressure steam turbine.
(b) Pass-out condensing steam turbine systems, in which a proportion of the exhaust steam used by the turbine is extracted at an intermediate pressure. The remaining exhaust steam is fully condensed to hot water before being exhausted. This system is called a pass-out/condensing steam turbine.
(c) Gas turbine systems, in which fuel is combusted in a gas turbine and the exhaust gases are used to supply a waste heat boiler producing usable heat. Some exhaust gases may be used directly for process heat applications.
(d) Reciprocating engine systems, which produce two grades of waste heat: high grade heat from the engine exhaust and low grade heat from the engine cooling circuits.
(e) Combined-cycle systems, where the exhaust gases from a gas turbine are used to power a steam turbine for conjoint electricity generation. Some further discussion of this is given in Sec. 4.6.2 of Chapter 4.

3.8.1. *CHP in the UK*

Some statistics of CHP plant ratings in the UK are given in Table 3.5 [6]. Most plants use fossil fuels but the use of biofuels such as sewage gases and municipal waste incinerator gases is increasing. Each of the five forms of CHP plants described above contributes significantly to overall efficiency improvement and energy saving. The main feature of the larger scale CHP market in the past ten years has been the increasing use of gas turbines. For steam-turbine-based plants the major fuel is coal. It is seen from Table 3.5 that in 2000 the UK had 1566 CHP plants with a total generating capacity of 4632 MW_e (i.e. megawatts electrical).

Growth in CHP continues in the UK, with an increase in capacity of 9% in 2000. While just under 50% of the CHP installations in the UK are small schemes with an electrical capacity of less than 100 kW_e, schemes larger than 10 MW_e account for over 80% of the total CHP installed electrical capacity. In 2000, 6% of the total electricity generated in the UK came from CHP plants. The UK government has

Table 3.5. CHP plants in the UK [6].

	1995	1998	1999	2000
CHP electrical capacity	3,094 MW_e	3,759 MW_e	4,004 MW_e	4,632 MW_e
CHP electricity generation	14,468 GWh	8,836 GWh	20,477 GWh	23,295 GWh
CHP heat generation	57,401 GWh	62,802 GWh	61,203 GWh	61,513 GWh
Number of CHP sites				
Less than 100 kW_e	686	696	694	724
100 kW_e to 999 kW_e	411	491	514	559
1 MW_e to 9.9 MW_e	147	175	177	196
10 MW_e and greater	64	73	75	77
Total	1,308	1,435	1,460	1,566

confirmed its new target of at least 10,000 MW_e of CHP by 2010 as part of its Climate Change Programme, and the previous target of 5000 MW_e is now expected to be met during 2001 [6].

The overall efficiency of the CHP option in terms of primary energy input to electricity/heat output is often claimed to be 70% or more — double the value from a conventional coal-fired plant. In addition to the more efficient use of fuels, CHP systems produce fewer air pollutants and lower thermal discharges than equivalent single-purpose systems. Initial cost is a disincentive to their introduction but as fuel prices rise the savings due to CHP increasingly offset the first costs.

Many district heating schemes, where the heat is centrally generated and piped to a distribution of local users, are combined with CHP schemes in the UK [13, 14].

3.8.2. *CHP in the USA* [15]

The historically first commercial electricity power plant in the USA — Thomas Edison's Pearl Street station in Manhattan, New York, in 1881 — was a CHP facility. Many of the early US electricity generation schemes were industrial facilities that added generators to existing steam systems. Gradually the use of CHP facilities declined as the use of large power plants developed at sites remote from their customers.

In the year 2002 the total electric power capacity in the USA exceeded 770 GW with about 54 GW, or 7%, due to CHP facilities. A comparison of the US position with some other industrial countries is shown in Fig. 3.12.

In the US thermal losses in power plants totalled 23 quadrillion BTUs of energy in 1997, representing 24% of the total US energy consumption. This amount of wasted energy is almost equal to the amount of energy used to fuel the entire US transportation sector. Also, vast new power generation assets are needed by 2010 to meet the anticipated increase of demand for electricity. A joint objective of the US Department of Energy's Office of Energy Efficiency and Renewable Energy and the CHP industry is to double the CHP capacity by the year 2010 [15].

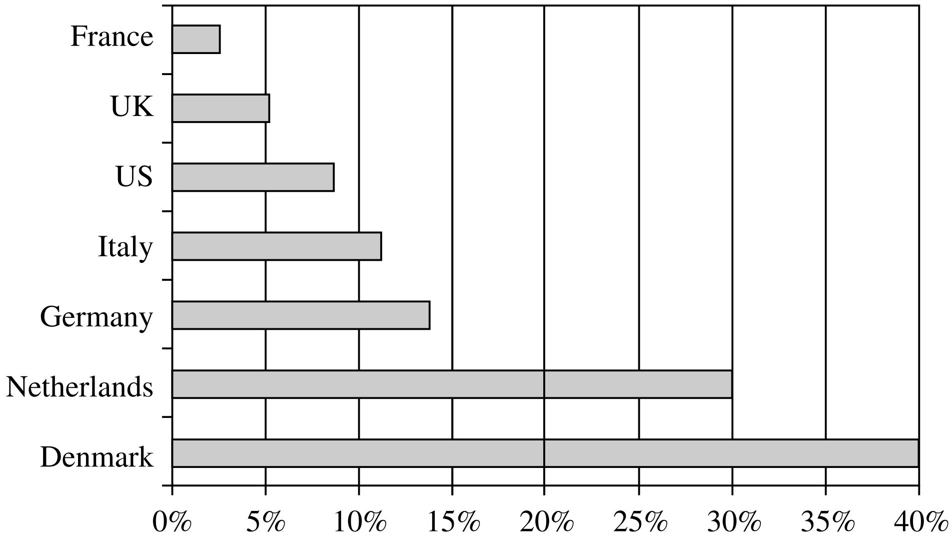


Fig. 3.12. CHP electrical power production [15] (per cent of total generation).

3.9. Efficient Utilisation of Electrical Energy

It is in the interests of everyone (except, perhaps, the vendors of prime fuels) that electricity should be used efficiently. This accomplishes the twin objectives of saving money and conserving prime energy.

Among the many features that might be addressed with regard to efficient utilisation are [16]:

(a) avoiding waste
(b) monitoring and control
(c) redesigning to reduce energy costs
(d) maintenance of equipment
(e) power factor correction
(f) maintenance of supply current waveform
(g) choice and use of electric motors
(h) load factor
(i) choice of lighting systems

3.9.1. *Avoiding waste*

It is a waste of fuel and money to leave electric lights or machines switched on unnecessarily, to overheat buildings, to have too much ventilation, etc.

3.9.2. *Monitoring and control*

Continuous human or automatic monitoring of an environment will eliminate the input of excess energy and reduce the need for emergency intervention.

3.9.3. *Redesigning to reduce energy costs*

It is good engineering practice to consider the energy costs of a machine or process. When different options are available it may become economical to replace an energy-inefficient machine with a more costly but efficient one.

3.9.4. *Maintenance of equipment*

The carrying out of regular, planned routine maintenance is essential to efficient operation. Records of the life cycles, performances and replacements of components need to be known.

3.9.5. *Power factor correction*

The power factor of a load usually indicates the ratio of power to current. For economic operation this ratio should be as near as possible to its maximum realisable per-unit value of unity. Continuous operation with a poor (i.e. low) power factor is extremely wasteful and expensive. Small, fully loaded AC induction motors can have power factors below 0.6 and, at low torque load, the power factor can drop to 0.1, especially for low speeds of operation. Power factor correction can be obtained by connecting suitable capacitors in parallel with the motor load. If the compensating capacitors are connected across the motor terminals, the wiring all the way back to the generating station is relieved. The reduction of supply currents causes reduced voltage (IR) drop and reduced resistance loss (I^2R) in the line conductors. Also the reduction of maximum demand of voltamperes may be an economic advantage to the customer in some electrical utility tariff structures. Power factor correction equipment is expensive and careful calculation is required to determine if it would be an economic investment.

3.9.6. *Maintenance of supply current waveform*

Many modern electrical AC loads cause deformation from the ideal sinusoidal current waveform. Large industrial loads such as arc furnaces and arc welders draw distorted current but so do television sets and personal computers. The combined effects of very many small distorting appliances can be worse than the effects of one very large industrial process. Distortion of the current waveform causes wastage of electrical energy plus other serious problems [17].

3.9.7. *Choice and use of electric motors*

The highest efficiency is achieved when an electric motor is the right size and operates at its rated load and speed. A motor purchase price varies directly with its rating (and size) so that oversizing is uneconomical in first cost and in running costs. Operation of a motor at reduced speed or reduced torque load is accompanied by loss of efficiency.

3.9.8. *Load factor*

Load factor is concerned with variations of electrical load on the supply network, usually on an hourly, daily or weekly basis. It can be defined as the ratio of average demand to maximum demand. In all types of operation high load factors are economically desirable, which implies steady and predictable load demand.

3.9.9. *Choice of lighting systems*

Different forms of electric light bulbs of the same rating give different amounts and qualities of illumination. The effectiveness of a lamp is sometimes called its efficacy and is a measure of the illumination in lumens per watt of electrical power input. Also relevant is the life expectancy of a typical lamp. Some typical values are given in Table 3.5 [18]. An installation of electric lighting is typical of engineering systems in that careful calculation has to be made of the initial costs, running costs, anticipated lifetime and replacement costs. A judgement of the overall quality of a lighting system is not only technical but psychological. The colour and shadowing effects are important factors in its acceptability.

Many countries have regulations specifying the minimum illumination, in lumens/unit area, to be used for various grades of accommodation such as factories, offices and classrooms. Appropriate figures for (as an example) the USA are given in Ref. 19.

Example 3.5

A factory building of area 6000 m^2 is lighted by 200 twin-tube fluorescent fixtures. Each tube is rated at 80 W, has an efficacy of 60 lumens/watt and a life expectancy of 8000 hours. Each fluorescent tube costs £4. It is intended that the lighting system be replaced to reduce running costs. The proposed new system would use 40 high pressure sodium lamps rated at 550 W, efficacy 100 lumens/watt with a life expectancy of 10,000 hours. Each sodium lamp costs £5. The factory is lighted for 12 hours/day, 5 days/week, 50 weeks/year. The labour charge for the replacement of a tube or lamp at any fixture is £5. The relevant electricity tariff is 6.3 p/unit (i.e. 6.3 p/kWh).

(a) Calculate the annual electricity bill for the two systems and the total cost saving due to changing to the sodium system.
(b) If the installation of the sodium lighting system would cost £3000, evaluate the break-even time. Neglect the effects of inflation and depreciation and write off any scrap value of the fluorescent system.
(c) Calculate the percentage increase in illumination in the factory.

The lights are in use for

$$12 \times 5 \times 50 = 3000 \text{ hours/year}$$

(a) For ease of comparison the various stages of the solution are evaluated in parallel vertical columns.

	Fluorescent System	Sodium System
Units of electricity used/year	$200 \times 2 \times 80 \times 3000$ $= 96{,}000{,}000$ Wh $= 96000$ kWh	$40 \times 550 \times 3000$ $= 66{,}000{,}000$ Wh $= 66000$ kWh
Annual electricity bill	$96000 \times 6.3/100$ $=$ £6048	$66000 \times 63/100$ £4158
Lamp/tube replacement period = life expectancy annual "on" time	$8000/300 = 2\frac{2}{3}$ years	$10000/3000 = 3\frac{1}{3}$ years
Labor cost of lamp/tube replacement	$\frac{200 \times 5}{2\frac{2}{3}} =$ £375/year	$\frac{40 \times 5}{3\frac{1}{3}} =$ £60/year
Equipment replacement costs/year	$\frac{200 \times 2 \times 4}{2\frac{2}{3}} =$ £600	$\frac{40 \times 25}{3\frac{1}{3}} =$ £300

The annual cost saving due to changing to sodium lights:

electricity bill	$6048 - 4158 = 1890$
labour charge	$375 - 60 = 315$
equipment replacement	$600 - 300 = 300$
Total Saving	$=$ £2505

(b) The capital cost of installing a new system is £3000 so that the payback for this investment is $\frac{3000}{2505} = 1.2$ years.
Such a short payback period represents a terrific bargain in commercial terms!

(c)

	Fluorescent	Sodium
Level of illumination per unit area = $\frac{\text{lamps} \times \text{rating} \times \text{efficacy}}{\text{area}}$	$\frac{200 \times 2 \times 80 \times 60}{6000}$ $= 320\ \text{lm/m}^2$	$\frac{40 \times 550 \times 100}{6000}$ $= 366.7\ \text{lm/m}^2$

The proposed change to sodium lighting therefore represents energy saving, annual cost saving, 14.6% increased illumination, and would repay the investment cost in 1.2 years.

3.10. Problems and Review Questions

Problems on electrical circuits and systems

3.1. A 200 V DC supply is applied to a resistor of value 1000 ohms. Calculate the current and power dissipation.

3.2. An electrical supply of 240 V is applied to a resistor resulting in a current of 12 A. Calculate the value of the resistor and the power dissipation.

3.3. When an electrical supply of 240 V, 50 Hz was applied to an electrical load the ammeter and wattmeter gave readings of 10 A and 750 W respectively. Calculate the circuit impedance and the power factor.

3.4. A DC electric motor rated at 2 HP is connected to a 200 V DC supply. If the input current at full load is 10 A, what is the motor efficiency?

3.5. A 120 V, 60 Hz electrical supply is applied to a single-phase AC motor rated at 2 HP. If the full-load current is 20.7 A and power input is 2000 W, calculate the motor efficiency and the power factor.

3.6. If the power factor for Problem 3.5 is improved to unity by the connection of parallel capacitors, what will be the new value of the current?

3.7. Why are AC generators and power transmission systems usually three-phase in nature?

3.8. Why do long-distance electrical transmission lines usually operate at high voltages?

3.9. Briefly discuss some of the main considerations in choosing a suitable location and site for an electrical power generation plant.

3.10. Which countries of the world consume the most electricity at present?

3.11. List the countries or regions that have the highest consumption of electricity per capita. Why does Canada have such a high per capita consumption?

3.12. Compare the total of world prime fuels used for electricity generation in 1996 with the projected figures for 2020. What are the trends in prime fuel use?

3.13. Compare the proportions of prime fuels used for electricity generation in the UK between 1980 and 1999. What are the present trends?

3.14. Compare the proportions of prime fuels used for electricity generation in the USA between 1990 and 2000.

3.15. What proportion of the total electricity consumption in the UK is now attributable to imported electricity? Where is the electricity imported from?

3.16. What proportion of the total electricity generation in the UK was attributable to combined heat and power schemes (a) in 1998, (b) in 2000?

3.17. What proportion of the total electricity generation in the USA was contributed by CHP schemes in the past year?

3.18. Explain, using a diagram, the principle of Combined Heat and Power Schemes. What improvement of overall efficiency can be obtained compared with a conventional coal-fired electricity generation plant?

3.19. Why is operating an unnecessarily oversized electric motor uneconomical?

3.20. The data of Table 3.6 suggests that high pressure sodium lighting has the highest efficacy and illuminance. Does it have any disadvantages?

3.21. A classroom of area 150 m^2 is illuminated by 20 standard incandescent lamps rated at 100 W with an illuminance of 1200 lumens and an efficacy of 12 lm/W. Each lamp costs 50 p and is switched on for 8 hours/day, 5 days/week, 40 weeks/year.

(a) If electricity costs 7 p/kWh, calculate the annual running cost.
(b) If the life expectancy of a lamp is 1000 hours and the replacement labour cost is £5 per item, calculate the annual replacement cost.
(c) Calculate the total annual electricity costs.

3.22. An alternative plan to light the classroom of Problem 3.21 is to use 30 fluorescent tubes, rated at 70 W with an illuminance of 4500 lumens and an efficacy of 64 lumens/watt. Each fluorescent tube costs £4 and has a life expectancy of 10,000 hours.

Table 3.6. Properties of types of electric lamps [18].

Type	Illuminance (lm)	Power (W)	Efficacy (lm/W)	Life expectancy (h)
Tungsten GLS	1,200	100	12	1,000
Tungsten halogen	50,000	2,000	25	4,000
Compact fluorescent	1,200	28	43	8,000
Fluorescent tube	4,500	70	64	10,000
High frequency tube	5,000	62	80	10,000
High pressure sodium	25,000	280	90	12,000

(a) Calculate the annual running costs if the electricity tariff is 7 p/kWh.
(b) Calculate the annual replacement cost if the replacement labour charge remains at £5 per item.
(c) Calculate the total annual electricity costs.

3.23. Compare the performances of the incandescent lamp system of Problem 3.21 with the corresponding fluorescent lamp system of Problem 3.22.

(a) What would be the annual cost saving in moving to the fluorescent system?
(b) The cost of the modified installation would be £660. Neglecting the effects of inflation and depreciation and ignoring any scrap value of the incandescent system, what would be the payback period of the modification?
(c) Compare the illuminance of the classroom using the two systems.

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CHAPTER 4

COAL

4.1. Introduction

4.1.1. *Composition and ranking of coal*

Coal is a hard, combustible, sedimentary rock. In spite of centuries of use its chemical nature is not fully understood. It is a very complex and varied substance with a quality determined by two classes of material: (a) the organic remains of plants solidified by the combined action of heat and pressure, and (b) inorganic substances contributed by the plants, water seepage and surrounding geological mineral matter. The organic content consists mostly of carbon plus smaller amounts of nitrogen, hydrogen and oxygen. The inorganic or mineral content, which is of the order 9–30% of the coal by weight, contains sulphur plus small but potentially toxic amounts of antimony, arsenic, beryllium, cadmium, mercury, lead, selenium, zinc, heavy radionuclides and asbestos [1].

When coal is heated many products arise, some of which are useful but some are potentially hazardous. Gases such as carbon monoxide, carbon dioxide, methane and water vapour are formed as the hydrogen and oxygen are driven off. The solid combustible residue remaining after the gases are burned off is called "fixed carbon" [2].

During coal formation, as the materials undergo evolutionary change from dead vegetation to coal, they pass through various stages of "coalification". This becomes the basis on which various categories of coal can be ranked, according to their calorific (i.e. heating) value and carbon-hydrogen ratios. Table 4.1 gives a ranking from the oldest formation, anthracite, with its low volatility and high carbon content, to the youngest formation, lignites [2]. Anthracite is the slowest- and cleanest-burning coal. Low volatile bituminous coal creates less ash than anthracite and is the best coal for making coke, which is a solid fuel that remains when coal is heated to a high temperature out of contact with air, as in the manufacture of coal gas. Coke is widely used in the manufacture of iron and steel in coke-oven plants.

Table 4.1. Classification of coal by rank [2].

Class	Carbon %	Hydrogen %	Fixed Carbon %	Calorific value MJ kg^{-1}
Anthracite	95–98	2.9–3.8	91–95	> 32.5
Low volatile bituminous	91–92	4.2–4.6	80–85	> 32.5
Medium volatile bituminous	87–92	4.6–5.2	70–80	> 32.5
High volatile bituminous	82.5–87	5.0–5.6	60–70	26.7–32.5
Sub-bituminous	78–82.5	5.2–5.6	55–60	19.3–26.7
Lignites	73–78	5.2–5.6	50–55	< 19.3

It can be seen in Table 4.1 that there can be a factor of 2:1 in calorific value between the best and worst of the fuel coals. Anthracite is classed as a “hard” coal, whereas lignites are classed as a “soft” coal.

4.1.2. *Coal mining*

Coal is extracted from the ground by (a) deep mining or (b) surface (open-cast) mining. In the deep mining process vertical shafts are sunk to the level of the coal seams, sometimes more than 4000 ft deep, and horizontal bores are then made along the seams. The shaft of a deep mine is identifiable by the surface winding-gear structure, Fig. 4.1 [3]. It is necessary to support the roofs of the diggings by pit-props to prevent collapse. The extracted rock and coal is transported by conveyer belts to the shafts and then taken to the surface. About 50–60% of a deep-mine seam content can be extracted.

The area around a developed deep mine is often identifiable by huge mounds of diggings, known in the UK as slag heaps. Nowadays these are covered with soil and grass in an attempt to minimise the visual environmental impact. Working in a deep coal mine is not only a very dirty occupation but can be unhealthy and dangerous. Deep mining involves the release of various gases, including carbon monoxide and methane, which represent serious explosion and underground fire risks.

The rates of fatalities and serious accidents in the coal industry are among the worst of all industries. In the USA, about 10 times as many accidental deaths occur in the coal energy cycle, from mine to power plant, as in the production of the equivalent amount of power from oil, gas and nuclear fuels together. A methane explosion at the Millfield mine in Southern Ohio, USA, in 1930, killed 82 people, including 73 miners, 5 mine officials and 4 visitors.

Until the period of the Second World War (1939–45), there were about 50 fatalities each year in the UK coal industry. On several occasions serious fires

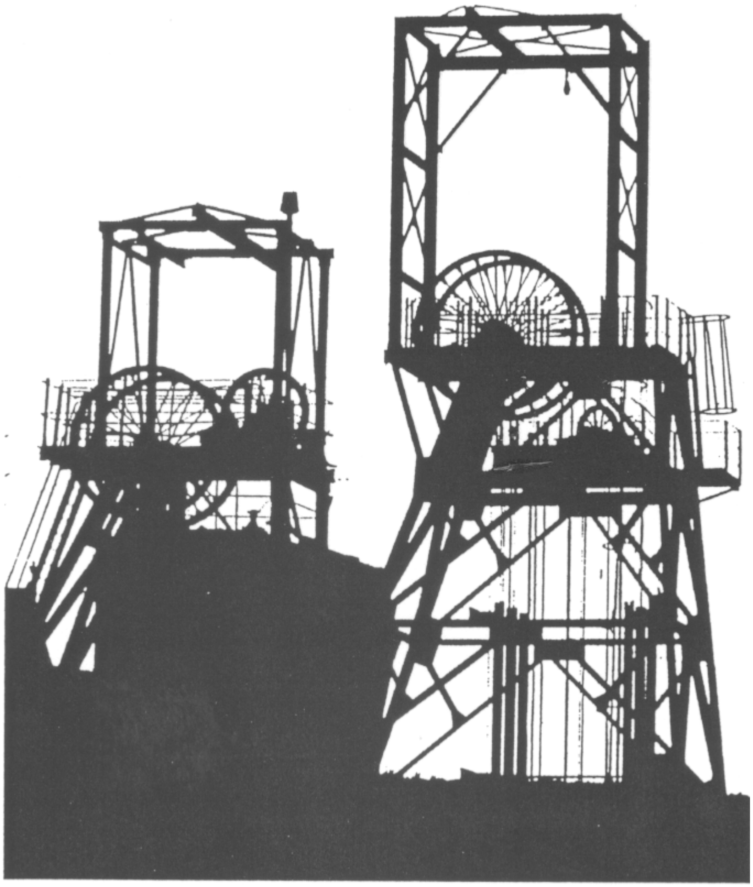


Fig. 4.1. Winding gear at the head of a deep mine [3].

and underground explosions caused the deaths of dozens of miners. The UK coal industry passed from private to public ownership in 1947 and thereafter the safety record improved. Working conditions in the mines have also improved drastically with increasing mechanisation, Fig. 4.2, and better underground ventilation. There is also now a much lower incidence of crippling accidents and industrial lung diseases such as silicosis and pneumoconiosis (black lung disease).

Coal seams are commonly 5–50 ft in thickness but may extend for miles horizontally.

When the coal seams are within about 200 ft of the surface it is possible to mine it by open-cast or surface methods. This involves the despoilation of large areas of ground that may not be reclaimable after the seams are exhausted. The process of extraction involves conventional earth-moving equipment and "draglines" — enormous shovels with a boom 180–375 ft long and a bucket that will hold up

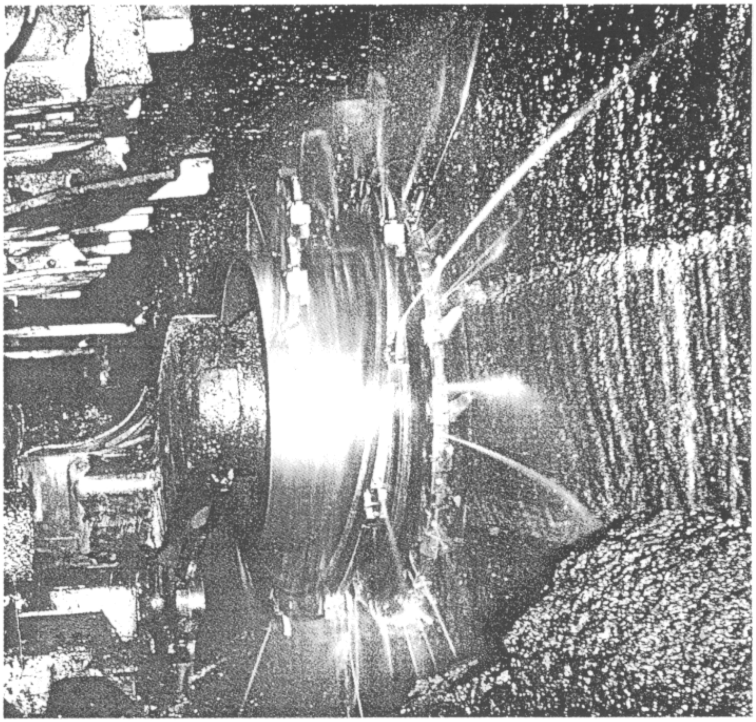


Fig. 4.2. Mechanised coal extraction in a deep mine [3].

to 5400 cubic feet of material. Open-cast-mined coal is cheaper to obtain than deep-mined coal, even after factoring in the reclamation costs. In the UK about 40% of the home-produced coal in 1999 was obtained by open-cast methods [4]. Surface mining has a bigger extraction yield than deep-mining and up to 90% of a seam content may be removed. In the former Soviet Union, the USA and Australia surface mine production now greatly exceeds deep mine production.

4.2. World Reserves, Production, and Consumption of Coal

4.2.1. *World coal reserves*

World coal reserves are widely distributed and are accessible by existing mining methods, Figs. 4.3 and 4.4. Unlike the situation for oil and gas, the coal reserves are spread fairly evenly in different parts of the world. The biggest repositories are the USA and the former Soviet Union, followed by China, Australia and India. Some further country-by-country detail is given in Table 4.2. The reserve/production (R/P) figures in years of reserves remaining are also included in Table 4.2 for the main areas of the world and some of this is also illustrated in Fig. 2.3 of Chapter 2.

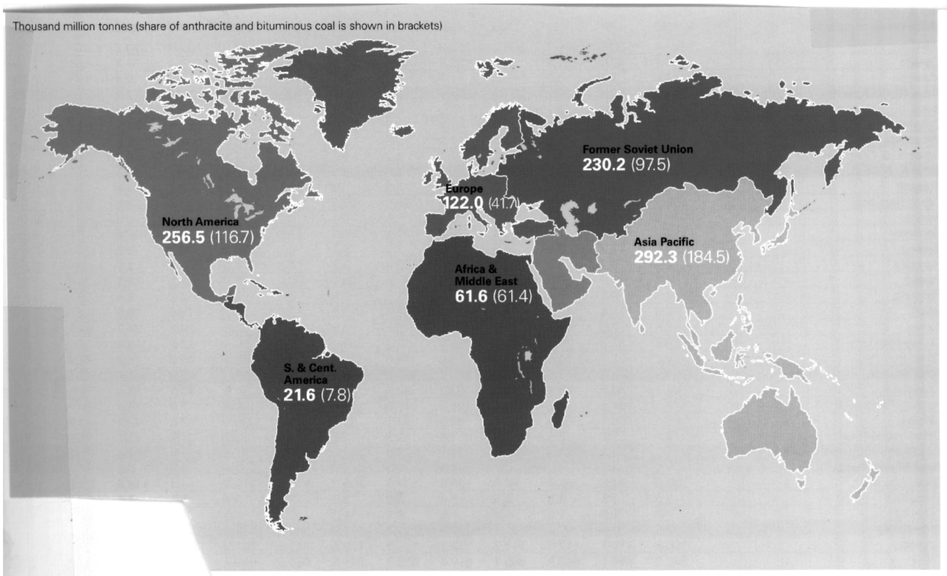
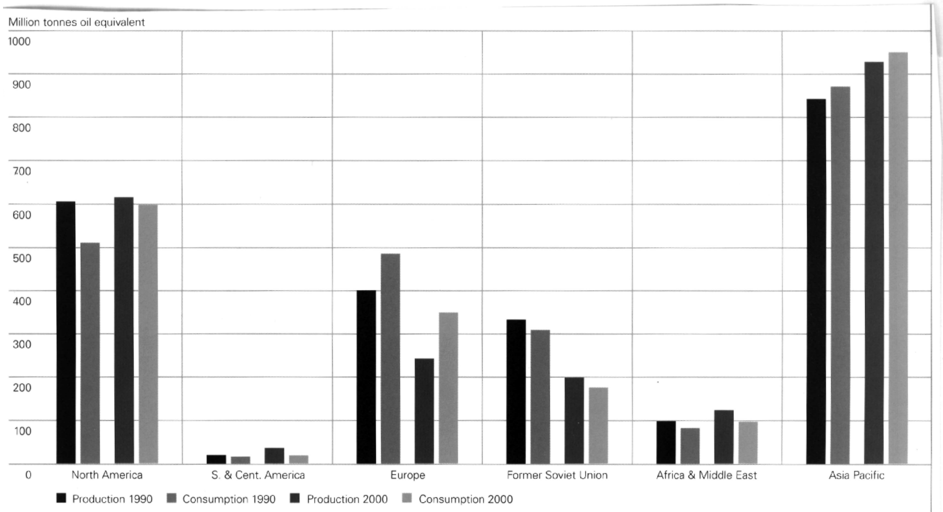

Thousand million tonnes (share of anthracite and bituminous coal is shown in brackets)
North America
256.5 (116.7)
S. & Cent. America
21.6 (7.8)
Europe
122.0 (41.7)
Africa & Middle East
61.6 (61.4)
Former Soviet Union
230.2 (97.5)
Asia Pacific
292.3 (184.5)

Fig. 4.3. World proven coal reserves, 2000 [5].



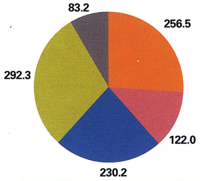
North American net coal exports have fallen steeply over the last 10 years as steady consumption growth has outstripped almost static production. Net exports from South and Central America and from Africa have increased considerably over the same period. European coal production has fallen even faster than consumption, increasing European net import requirements.

Fig. 4.4. Production and consumption of coal, 1990 and 2000 [5].

Table 4.2. World coal reserves, 2000 [5].

Distribution of reserves 2000

Thousand million tonnes



		%
🟧 North America	256.5	26.1
🟥 Europe	122.0	12.4
🟦 Former Soviet Union	230.2	23.4
🟨 Asia Pacific	292.3	29.7
■ Rest of World	83.2	8.4

Notes

Proved reserves of coal
Generally taken to be those quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known deposits under existing economic and operating conditions.

Reserves/Production (R/P) ratio
If the reserves remaining at the end of any year are divided by the production in that year, the result is the length of time that those remaining reserves would last if production were to continue at that level.

Source of reserves data
World Energy Council.

Million tonnes	Anthracite and bituminous	Sub-bituminous and Lignite	Total	Share of total	R/P ratio
USA	111338	135305	246643	25.1%	253
Canada	4509	4114	8623	0.9%	125
Mexico	860	351	1211	0.1%	121
Total North America	116707	139770	256477	26.1%	243
Brazil	–	11950	11950	1.2%	*
Colombia	6368	381	6749	0.7%	177
Venezuela	479	–	479	0.1%	56
Other S. & Cent. America	992	1404	2396	0.2%	*
Total S. & Cent. America	7839	13735	21574	2.2%	405
Bulgaria	13	2698	2711	0.3%	103
Czech Republic	2613	3564	6177	0.6%	95
France	95	21	116	†	32
Germany	24000	43000	67000	6.8%	333
Greece	–	2874	2874	0.3%	47
Hungary	596	3865	4461	0.4%	322
Poland	12113	2196	14309	1.4%	88
Romania	1	3610	3611	0.4%	123
Spain	200	460	660	0.1%	29
Turkey	449	626	1075	0.1%	16
United Kingdom	1000	500	1500	0.2%	47
Other Europe	584	16954	17538	1.8%	335
Total Europe	41664	80368	122032	12.4%	165
Kazakhstan	31000	3000	34000	3.5%	455
Russian Federation	49088	107922	157010	15.9%	*
Ukraine	16388	17968	34356	3.5%	423
Other Former Soviet Union	1000	3812	4812	0.5%	*
Total Former Soviet Union	97476	132702	230178	23.4%	*
South Africa	55333	–	55333	5.6%	247
Zimbabwe	734	–	734	0.1%	177
Other Africa	5095	250	5345	0.5%	*
Middle East	193	–	193	†	193
Total Africa & Middle East	61355	250	61605	6.2%	266
Australia	47300	43100	90400	9.2%	297
China	62200	52300	114500	11.6%	116
India	72733	2000	74733	7.6%	223
Indonesia	770	4450	5220	0.5%	68
Japan	785	–	785	0.1%	249
New Zealand	29	542	571	0.1%	159
North Korea	300	300	600	0.1%	8
Pakistan	–	2928	2928	0.3%	*
South Korea	82	–	82	†	20
Other Asia Pacific	251	2275	2526	0.2%	70
Total Asia Pacific	184450	107895	292345	29.7%	159
TOTAL WORLD	**509491**	**474720**	**984211**	**100.0%**	**227**
of which: OECD	206483	240617	447100	45.4%	223
Other EMEs‡	205448	78238	283686	28.8%	157

*More than 500 years.
†Less than 0.05.
‡Excludes Central Europe and Former Soviet Union.

Anthracite and bituminous coal, with its high heat energy value, is widely traded around the world. Lignite or "brown coal" is not traded to any significant extent in world markets because of its relatively low heat content. The present (2002) figures of reserves suggest that coal will far outlast both oil and natural gas as a primary fuel source. The widespread nature of the deposits will hopefully prevent any violent political or military action to gain control over the remaining coal. Nevertheless, there are wide disparities between different countries. If the indigenous reserves remaining are divided by the current production figures to give the present (2002) R/P ratios, these indicate the needs/opportunities to participate in trading in the world coal market. For example, the European countries France, Greece, Spain, Turkey and the UK have less than 50 years of reserves remaining, Table 4.2. On the other hand, there are many countries, including the USA, that have more than 200 years of reserves at present rates of usage. It is quite likely that estimates of coal reserves might reduce in the future as coal is used to offset the demand for depleting reserves of oil and natural gas. Although the coal will outlast the fluid fuels, it too will eventually run out. A need exists for the conservation of coal supplies and also for the continual exploration of more efficient methods of coal use.

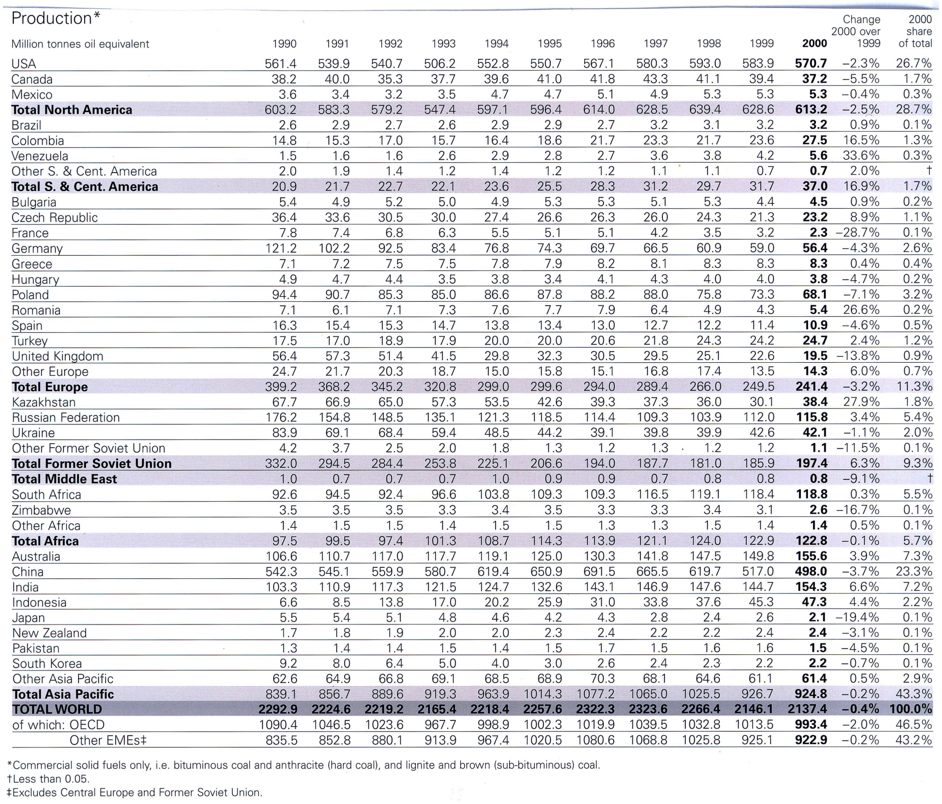
4.2.2. *World coal production*

Details of country-by-country coal production between 1990 and 2000 are given in Table 4.3 [5]. Over that 11-year period world coal production fell by 6.8%, North American production slightly increased and European production fell by almost 40% of the 1990 figure due to cutbacks by the big producers the Czech Republic, Germany, Poland and the UK. Production in the Pacific region increased due to increases for Australia and India of around 50%. Details of the production changes in the period 1990–2000 for the major areas of the world are shown in Table 4.4.

Coal subsidies continue to support the high-cost production of hard coal in Germany, Spain and France. For 1996, the European Commission authorised coal industry subsidies, detailed in reference [7]. In each country, the average subsidy per ton of coal produced exceeds the average value of imported coal. Recent agreements between the governments, mining companies and labour unions on future coal production subsidies indicate that further declines in output are forthcoming. In the UK, production subsidies have been phased out, forcing coal producers into direct competition with North Sea gas and international coal [6]. In the USA President Bush recently (2002) offered support to the coal industry by the promise of possible increases of production.

Table 4.5 shows the world export/import situation for coal in 1999 with projections to 2010 and 2020. The terms "steam" and "coking" coal both refer to the high grade coal used in electricity power generation. Australia, the USA and Canada have substantial reserves of premium coals that can be used to manufacture coke.

Table 4.3. Coal production (mtoes), 1990–2000 [5].



Production* Million tonnes oil equivalent	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	**2000**	Change 2000 over 1999	2000 share of total
USA	561.4	539.9	540.7	506.2	552.8	550.7	567.1	580.3	593.0	583.9	**570.7**	–2.3%	26.7%
Canada	38.2	40.0	35.3	37.7	39.6	41.0	41.8	43.3	41.1	39.4	**37.2**	–5.5%	1.7%
Mexico	3.6	3.4	3.2	3.5	4.7	4.7	5.1	4.9	5.3	5.3	**5.3**	–0.4%	0.3%
Total North America	603.2	583.3	579.2	547.4	597.1	596.4	614.0	628.5	639.4	628.6	**613.2**	–2.5%	28.7%
Brazil	2.6	2.9	2.7	2.6	2.9	2.9	2.7	3.2	3.1	3.2	**3.2**	0.9%	0.1%
Colombia	14.8	15.3	17.0	15.7	16.4	18.6	21.7	23.3	21.7	23.6	**27.5**	16.5%	1.3%
Venezuela	1.5	1.6	1.6	2.6	2.9	2.8	2.7	3.6	3.8	4.2	**5.6**	33.6%	0.3%
Other S. & Cent. America	2.0	1.9	1.4	1.2	1.4	1.2	1.2	1.1	1.1	0.7	**0.7**	2.0%	†
Total S. & Cent. America	20.9	21.7	22.7	22.1	23.6	25.5	28.3	31.2	29.7	31.7	**37.0**	16.9%	1.7%
Bulgaria	5.4	4.9	5.2	5.0	4.9	5.3	5.3	5.1	5.3	4.4	**4.5**	0.9%	0.2%
Czech Republic	36.4	33.6	30.5	30.0	27.4	26.6	26.3	26.0	24.3	21.3	**23.2**	8.9%	1.1%
France	7.8	7.4	6.8	6.3	5.5	5.1	5.1	4.2	3.5	3.2	**2.3**	–28.7%	0.1%
Germany	121.2	102.2	92.5	83.4	76.8	74.3	69.7	66.5	60.9	59.0	**56.4**	–4.3%	2.6%
Greece	7.1	7.2	7.5	7.5	7.8	7.9	8.2	8.1	8.3	8.3	**8.3**	0.4%	0.4%
Hungary	4.9	4.7	4.4	3.5	3.8	3.4	4.1	4.3	4.0	4.0	**3.8**	–4.7%	0.2%
Poland	94.4	90.7	85.3	85.0	86.6	87.8	88.2	88.0	75.8	73.3	**68.1**	–7.1%	3.2%
Romania	7.1	6.1	7.1	7.3	7.6	7.7	7.9	6.4	4.9	4.3	**5.4**	26.6%	0.2%
Spain	16.3	15.4	15.3	14.7	13.8	13.4	13.0	12.7	12.2	11.4	**10.9**	–4.6%	0.5%
Turkey	17.5	17.0	18.9	17.9	20.0	20.0	20.6	21.8	24.3	24.2	**24.7**	2.4%	1.2%
United Kingdom	56.4	57.3	51.4	41.5	29.8	32.3	30.5	29.5	25.1	22.6	**19.5**	–13.8%	0.9%
Other Europe	24.7	21.7	20.3	18.7	15.0	15.8	15.1	16.8	17.4	13.5	**14.3**	6.0%	0.7%
Total Europe	399.2	368.2	345.2	320.8	299.0	299.6	294.0	289.4	266.0	249.5	**241.4**	–3.2%	11.3%
Kazakhstan	67.7	66.9	65.0	57.3	53.5	42.6	39.3	37.3	36.0	30.1	**38.4**	27.9%	1.8%
Russian Federation	176.2	154.8	148.5	135.1	121.3	118.5	114.4	109.3	103.9	112.0	**115.8**	3.4%	5.4%
Ukraine	83.9	69.1	68.4	59.4	48.5	44.2	39.1	39.8	39.9	42.6	**42.1**	–1.1%	2.0%
Other Former Soviet Union	4.2	3.7	2.5	2.0	1.8	1.3	1.2	1.3	1.2	1.2	**1.1**	–11.5%	0.1%
Total Former Soviet Union	332.0	294.5	284.4	253.8	225.1	206.6	194.0	187.7	181.0	185.9	**197.4**	6.3%	9.3%
Total Middle East	1.0	0.7	0.7	0.7	1.0	0.9	0.9	0.7	0.8	0.8	**0.8**	–9.1%	†
South Africa	92.6	94.5	92.4	96.6	103.8	109.3	109.3	116.5	119.1	118.4	**118.8**	0.3%	5.5%
Zimbabwe	3.5	3.5	3.5	3.3	3.4	3.5	3.3	3.3	3.4	3.1	**2.6**	–16.7%	0.1%
Other Africa	1.4	1.5	1.5	1.4	1.5	1.5	1.3	1.3	1.5	1.4	**1.4**	0.5%	0.1%
Total Africa	97.5	99.5	97.4	101.3	108.7	114.3	113.9	121.1	124.0	122.9	**122.8**	–0.1%	5.7%
Australia	106.6	110.7	117.0	117.7	119.1	125.0	130.3	141.8	147.5	149.8	**155.6**	3.9%	7.3%
China	542.3	545.1	559.9	580.7	619.4	650.9	691.5	665.5	619.7	517.0	**498.0**	–3.7%	23.3%
India	103.3	110.9	117.3	121.5	124.7	132.6	143.1	146.9	147.6	144.7	**154.3**	6.6%	7.2%
Indonesia	6.6	8.5	13.8	17.0	20.2	25.9	31.0	33.8	37.6	45.3	**47.3**	4.4%	2.2%
Japan	5.5	5.4	5.1	4.8	4.6	4.2	4.3	2.8	2.4	2.6	**2.1**	–19.4%	0.1%
New Zealand	1.7	1.8	1.9	2.0	2.0	2.3	2.4	2.2	2.2	2.4	**2.4**	–3.1%	0.1%
Pakistan	1.3	1.4	1.4	1.5	1.4	1.5	1.7	1.5	1.6	1.6	**1.5**	–4.5%	0.1%
South Korea	9.2	8.0	6.4	5.0	4.0	3.0	2.6	2.4	2.3	2.2	**2.2**	–0.7%	0.1%
Other Asia Pacific	62.6	64.9	66.8	69.1	68.5	68.9	70.3	68.1	64.6	61.1	**61.4**	0.5%	2.9%
Total Asia Pacific	839.1	856.7	889.6	919.3	963.9	1014.3	1077.2	1065.0	1025.5	926.7	**924.8**	–0.2%	43.3%
TOTAL WORLD	**2292.9**	**2224.6**	**2219.2**	**2165.4**	**2218.4**	**2257.6**	**2322.3**	**2323.6**	**2266.4**	**2146.1**	**2137.4**	**–0.4%**	**100.0%**
of which: OECD	1090.4	1046.5	1023.6	967.7	998.9	1002.3	1019.9	1039.5	1032.8	1013.5	**993.4**	–2.0%	46.5%
Other EMEs‡	835.5	852.8	880.1	913.9	967.4	1020.5	1080.6	1068.8	1025.8	925.1	**922.9**	–0.2%	43.2%

*Commercial solid fuels only, i.e. bituminous coal and anthracite (hard coal), and lignite and brown (sub-bituminous) coal.
†Less than 0.05.
‡Excludes Central Europe and Former Soviet Union.

Table 4.4. Changes in coal production, 1999–2000.

Area	% Change (rounded)
North America	+2%
Europe	−40%
Czech Republic	−36%
Germany	−53%
Poland	−28%
UK	−65%
Asia Pacific	+10%
Australia	+50%
India	+49%
Indonesia	+617%
FSU	−41%
Africa	+26%
World	−7%

Table 4.5. World coal flows by importing and exporting regions, reference case, 2000, 2010 and 2020.

(Million Short Tons)

	Importers											
	Steam[a]				Coking				Total			
Exporters	Europe[b]	Asia	America	Total[c]	Europe[b]	Asia[d]	America	Total[c]	Europe[b]	Asia	America	Total[c]
						1999						
Australia	12.3	76.2	1.3	**87.4**	23.3	69.7	6.7	**102.0**	35.6	145.8	8.0	**189.4**
United States	4.9	4.5	17.1	**26.5**	19.4	4.1	8.7	**32.2**	24.3	8.6	25.8	**58.6**
South Africa......	49.3	19.0	1.7	**70.2**	0.9	0.8	0.8	**2.9**	50.2	19.7	2.4	**73.1**
Former Soviet Union .	12.1	4.9	0.0	**17.0**	2.6	2.9	0.0	**5.5**	14.7	7.7	0.0	**22.5**
Poland	14.0	0.0	0.0	**14.0**	3.3	0.0	0.7	**3.9**	17.3	0.0	0.7	**18.0**
Canada	0.1	4.5	0.7	**5.4**	6.9	20.1	2.8	**31.9**	7.1	24.6	3.4	**37.3**
China	3.4	31.5	0.4	**33.7**	0.2	6.9	0.0	**7.2**	3.6	38.4	0.4	**40.9**
South America[e]....	25.8	0.0	9.3	**38.7**	0.6	0.0	1.4	**1.8**	26.3	0.0	10.7	**40.5**
Indonesia[f].......	10.7	40.3	3.2	**57.2**	1.3	8.6	0.4	**11.1**	12.0	48.9	3.6	**68.3**
Total.........	**132.6**	**180.9**	**33.6**	**350.1**	**58.5**	**113.0**	**21.5**	**198.3**	**191.1**	**293.8**	**55.1**	**548.4**
						2010						
Australia	10.2	121.5	0.8	**132.4**	31.8	82.0	8.0	**121.7**	42.0	203.4	8.8	**254.2**
United States	5.0	7.7	9.7	**22.4**	18.9	1.3	15.0	**35.2**	23.8	9.1	24.7	**57.6**
South Africa......	49.6	28.9	4.6	**83.0**	1.0	6.1	0.0	**7.1**	50.5	35.0	4.6	**90.1**
Former Soviet Union .	12.1	2.8	0.0	**14.9**	1.5	0.0	0.0	**1.5**	13.7	2.8	0.0	**16.4**
Poland	8.0	0.0	0.0	**8.0**	3.6	0.0	0.0	**3.6**	11.7	0.0	0.0	**11.7**
Canada	5.1	3.3	0.0	**8.4**	4.6	20.1	2.8	**27.4**	9.6	23.4	2.8	**35.7**
China	1.2	65.1	0.0	**66.4**	0.0	8.3	0.0	**8.3**	1.2	73.4	0.0	**74.6**
South America[e]....	36.5	0.0	34.7	**71.2**	0.0	0.0	0.0	**0.0**	36.5	0.0	34.7	**71.2**
Indonesia[f].......	9.0	64.5	0.0	**73.5**	0.9	4.0	0.0	**5.0**	9.9	68.6	0.0	**78.5**
Total.........	**136.7**	**293.8**	**49.7**	**480.2**	**62.3**	**121.7**	**25.8**	**209.8**	**198.9**	**415.5**	**75.5**	**690.0**
						2020						
Australia	6.6	129.3	0.9	**136.8**	35.8	86.3	12.2	**134.3**	42.4	215.6	13.1	**271.1**
United States	2.9	8.6	10.2	**21.7**	15.2	1.5	17.7	**34.4**	18.1	10.1	28.0	**56.1**
South Africa......	46.7	38.1	4.2	**89.0**	0.0	6.6	0.0	**6.6**	46.7	44.7	4.2	**95.6**
Former Soviet Union .	12.1	3.9	0.0	**16.0**	1.5	0.0	0.0	**1.5**	13.7	3.9	0.0	**17.5**
Poland	5.5	0.0	0.0	**5.5**	3.4	0.0	0.0	**3.4**	8.9	0.0	0.0	**8.9**
Canada	5.1	1.6	0.0	**6.6**	4.3	19.9	1.5	**25.7**	9.3	21.5	1.5	**32.3**
China	3.4	70.7	0.0	**74.1**	0.0	8.8	0.0	**8.8**	3.4	79.5	0.0	**82.9**
South America[e]....	38.8	0.0	36.9	**75.7**	0.0	0.0	0.0	**0.0**	38.8	0.0	36.9	**75.7**
Indonesia[f].......	6.8	77.0	0.0	**83.8**	0.9	4.1	0.0	**5.0**	7.7	81.1	0.0	**88.8**
Total.........	**127.8**	**329.1**	**52.2**	**509.1**	**61.0**	**127.3**	**31.5**	**219.8**	**188.9**	**456.4**	**83.7**	**729.0**

[a] Reported data for 1999 are consistent with data published by the International Energy Agency (IEA). The standard IEA definition for "steam coal" includes coal used for pulverized coal injection (PCI) at steel mills; however, some PCI coal is reported by the IEA as "coking coal."

[b] Coal flows to Europe include shipments to the Middle East and Africa.

[c] In 1999, total world coal flows include a balancing item used by the International Energy Agency to reconcile discrepancies between reported exports and imports. The 1999 balancing items by coal type were 3.0 million tons (steam coal), 5.4 million tons (coking coal), and 8.4 million tons (total).

[d] Includes 9.7 million tons of coal for pulverized coal injection at blast furnaces shipped to Japanese steelmakers in 1999.

[e] Coal exports from South America are projected to originate from mines in Colombia and Venezuela.

[f] In 1999, coal exports from Indonesia include shipments from other countries not modeled for the forecast period. The 1999 non-Indonesian exports by coal type were 7.2 million tons (steam coal), 1.4 million tons (coking coal), and 8.6 million tons (total).

Notes: Data exclude non-seaborne shipments of coal to Europe and Asia. Totals may not equal sum of components due to independent rounding. The sum of the columns may not equal the total, because the total includes a balancing item between importers' and exporters' data.

Sources: **1999:** International Energy Agency, *Coal Information 2000* (Paris, France, August 2000); Energy Information Administration, *Quarterly Coal Report, October-December 1999*, DOE/EIA-0121(99/4Q) (Washington, DC, April 2000). **Projections:** Energy Information Administration, *Annual Energy Outlook 2001*, DOE/EIA-0383(2001) (Washington, DC, December 2000), National Energy Modeling System run AEO2001.D101600A.

Together, these three countries supplied 85% of the coking coal traded worldwide in 1997, Table 4.4 [6].

4.2.3. *World coal consumption*

World coal consumption is a source of heat energy plus chemical products. It has declined from 2270.3 mtoes in 1990 to 2186 mtoes in 2000, a reduction of 3.7% of

Table 4.6. Coal consumption (mtoes), 1990–2000 [5].

Million tonnes oil equivalent	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	**2000**	Change 2000 over 1999	2000 share of total
USA	482.3	478.5	482.7	498.1	502.3	504.6	528.1	540.9	543.2	546.4	**564.1**	3.3%	25.8%
Canada	24.4	25.5	26.2	23.7	24.5	25.2	25.7	26.8	28.1	27.8	**29.3**	5.5%	1.3%
Mexico	3.4	3.3	3.4	3.8	4.4	4.9	5.7	5.8	5.9	6.0	**6.1**	2.1%	0.3%
Total North America	510.1	507.3	512.3	525.6	531.2	534.7	559.5	573.5	577.2	580.2	**599.5**	3.3%	27.4%
Argentina	1.0	0.8	0.8	0.7	1.2	0.9	0.9	0.8	0.7	0.7	**0.7**	–	†
Brazil	9.5	10.2	9.9	10.2	10.2	10.7	11.2	11.4	11.2	11.7	**12.2**	3.9%	0.6%
Chile	2.4	2.0	1.8	1.8	2.2	2.4	3.2	4.2	3.7	4.3	**3.5**	–18.6%	0.2%
Colombia	3.5	3.7	3.6	3.7	3.6	3.4	3.2	3.1	2.8	2.1	**2.2**	5.6%	0.1%
Ecuador	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Peru	0.2	0.3	0.3	0.4	0.4	0.4	0.3	0.4	0.4	0.5	**0.5**	7.5%	†
Venezuela	0.2	0.2	0.3	0.2	0.2	0.2	0.2	0.3	0.3	0.3	**0.3**	–	†
Other S. & Cent. America	0.4	0.4	0.5	0.5	0.5	0.5	0.4	0.5	0.5	0.5	**0.5**	3.8%	†
Total S. & Cent. America	17.2	17.6	17.2	17.5	18.3	18.5	19.4	20.7	19.6	20.1	**19.9**	–0.8%	0.9%
Austria	3.6	3.6	2.8	2.4	2.5	2.4	2.7	3.1	3.0	3.2	**3.0**	–5.2%	0.1%
Belgium & Luxembourg	10.4	10.8	10.2	8.7	8.5	9.8	7.6	7.5	7.9	6.9	**7.3**	6.1%	0.3%
Bulgaria	8.9	7.5	7.3	8.2	7.6	7.8	8.4	7.8	8.2	6.6	**6.5**	–1.1%	0.3%
Czech Republic	33.5	30.4	25.4	23.7	22.0	20.9	21.6	21.2	19.5	17.1	**19.3**	12.5%	0.9%
Denmark	6.0	8.4	6.7	7.2	7.8	6.6	9.0	6.7	5.6	4.7	**4.0**	–14.8%	0.2%
Finland	3.3	3.6	2.7	3.1	4.1	3.1	4.0	4.5	3.4	3.6	**3.5**	–1.5%	0.2%
France	19.1	20.1	17.9	14.7	13.7	14.5	15.4	13.4	16.1	14.2	**14.0**	–1.0%	0.6%
Germany	129.6	113.3	104.4	97.9	95.6	90.6	89.9	86.8	84.8	80.2	**82.7**	3.1%	3.8%
Greece	8.0	7.8	8.4	7.9	8.4	8.2	7.8	7.6	8.8	8.8	**8.9**	0.5%	0.4%
Hungary	5.6	5.8	4.6	4.0	3.6	3.6	3.7	3.7	3.4	3.4	**3.2**	–6.1%	0.1%
Iceland	0.1	0.1	†	†	0.1	0.1	0.1	0.1	0.1	0.1	**0.1**	28.4%	†
Republic of Ireland	2.2	2.2	2.0	1.9	1.9	1.9	1.9	2.0	1.9	1.6	**1.7**	7.6%	0.1%
Italy	14.1	13.7	12.4	10.0	10.7	12.5	11.2	11.0	11.6	11.6	**11.7**	0.9%	0.5%
Netherlands	9.5	8.2	7.7	8.2	9.0	9.8	9.3	9.5	9.4	7.0	**7.9**	11.9%	0.4%
Norway	0.5	0.4	0.4	0.5	0.6	0.7	0.6	0.6	0.7	0.7	**0.7**	–0.3%	†
Poland	80.2	77.6	73.0	74.0	72.3	71.7	73.2	70.1	63.8	61.0	**57.1**	–6.4%	2.6%
Portugal	2.8	3.0	3.0	3.3	3.4	4.2	3.9	3.6	3.6	3.6	**3.6**	–0.2%	0.2%
Romania	11.7	9.6	10.3	9.5	9.4	9.7	9.5	8.4	7.0	6.7	**8.4**	25.0%	0.4%
Slovakia	6.9	6.3	6.2	5.6	5.0	5.1	5.0	4.7	4.5	4.8	**4.7**	–3.2%	0.2%
Spain	19.0	18.8	19.1	18.2	18.0	18.5	15.5	17.7	17.7	20.5	**21.6**	5.3%	1.0%
Sweden	2.2	2.4	2.2	2.1	2.1	2.1	2.4	2.1	2.0	2.0	**2.0**	2.3%	0.1%
Switzerland	0.3	0.3	0.2	0.1	0.2	0.2	0.1	0.1	0.1	0.1	**0.1**	–	†
Turkey	22.3	22.0	24.9	24.3	23.2	23.2	26.7	28.9	29.6	27.7	**27.2**	–1.8%	1.3%
United Kingdom	64.9	65.1	61.2	53.3	49.7	47.5	44.8	39.9	40.2	35.6	**37.7**	5.8%	1.7%
Other Europe	19.3	17.4	16.9	14.9	11.9	12.2	11.7	12.2	13.3	10.1	**10.5**	4.4%	0.5%
Total Europe	484.0	458.4	429.9	403.7	391.3	386.9	386.0	373.2	366.2	341.8	**347.4**	1.6%	15.9%
Azerbaijan	0.1	0.1	–	–	–	–	–	–	–	–	**–**	–	–
Belarus	1.2	1.1	0.7	0.6	0.2	0.3	0.5	0.6	0.4	0.1	**0.1**	–	†
Kazakhstan	40.2	38.2	39.9	36.4	34.5	27.5	25.9	22.4	22.9	19.8	**23.2**	16.9%	1.1%
Lithuania	0.6	0.6	0.5	†	0.1	0.1	0.1	0.1	0.1	0.1	**0.1**	–35.7%	†
Russian Federation	180.6	165.6	154.7	140.8	126.4	119.4	115.7	109.7	102.8	109.4	**110.4**	0.8%	5.0%
Turkmenistan	0.4	0.3	0.1	–	†	†	†	–	–	–	**–**	–	–
Ukraine	74.8	62.1	63.9	56.3	46.3	42.1	33.2	38.0	36.9	38.5	**38.8**	0.7%	1.8%
Uzbekistan	4.1	4.0	2.9	1.9	1.8	1.4	1.2	1.9	1.8	1.8	**1.6**	–12.5%	0.1%
Other Former Soviet Union	6.0	5.7	2.8	2.7	2.2	1.9	2.1	2.5	1.7	1.0	**0.8**	–23.0%	†
Total Former Soviet Union	308.0	277.7	265.5	238.7	211.5	192.7	178.7	175.2	166.6	170.7	**175.0**	2.4%	8.0%
Iran	1.1	1.1	1.2	1.3	1.3	1.4	1.2	0.9	1.0	1.0	**1.1**	3.1%	†
Kuwait	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Qatar	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Saudi Arabia	–	–	–	–	–	–	–	–	–	–	**–**	–	–
United Arab Emirates	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Other Middle East	2.3	2.5	3.1	3.5	3.8	4.1	5.0	5.4	5.8	5.7	**6.2**	9.1%	0.3%
Total Middle East	3.4	3.6	4.3	4.8	5.1	5.5	6.2	6.3	6.8	6.7	**7.3**	8.2%	0.3%
Algeria	0.5	0.6	0.5	0.5	0.5	0.4	0.4	0.3	0.5	0.3	**0.3**	–0.3%	†
Egypt	0.8	0.7	0.8	0.9	1.0	0.7	0.9	0.9	0.9	0.9	**0.9**	–	†
South Africa	71.3	70.1	67.3	69.8	73.6	77.4	81.7	84.3	83.4	82.1	**81.9**	–0.3%	3.8%
Other Africa	6.7	6.0	6.1	6.8	6.5	6.7	6.7	6.9	6.8	6.8	**6.6**	–3.1%	0.3%
Total Africa	79.3	77.4	74.7	78.0	81.6	85.2	89.7	92.4	91.6	90.1	**89.7**	–0.5%	4.1%
Australia	39.5	37.4	39.0	36.4	38.7	41.2	43.9	45.4	45.9	45.5	**46.7**	2.6%	2.1%
Bangladesh	0.3	0.1	0.1	†	†	†	0.2	0.3	0.1	0.2	**0.2**	16.7%	†
China	533.6	534.9	549.5	570.3	606.4	635.7	676.9	649.3	616.8	512.7	**480.1**	–6.4%	22.0%
China Hong Kong SAR	5.5	5.9	6.3	7.3	5.2	5.6	4.2	3.5	4.4	3.9	**3.7**	–5.2%	0.2%
India	106.2	114.4	121.4	125.9	131.6	140.2	151.7	157.4	157.1	154.5	**163.4**	5.8%	7.5%
Indonesia	4.0	4.1	4.1	4.0	4.8	5.3	7.8	8.3	9.5	10.5	**11.5**	9.5%	0.5%
Japan	76.0	79.0	78.0	79.2	82.0	86.2	88.3	89.8	88.4	91.5	**98.9**	8.1%	4.5%
Malaysia	1.3	1.3	1.3	1.3	1.1	1.5	1.5	1.1	1.2	1.2	**1.3**	8.3%	0.1%
New Zealand	1.3	1.2	1.3	1.2	1.2	1.2	1.2	1.2	1.1	1.2	**1.2**	–0.9%	0.1%
Pakistan	2.1	2.0	2.1	2.2	2.2	2.2	2.2	2.1	2.1	2.1	**2.1**	0.1%	0.1%
Philippines	1.0	1.3	1.1	1.3	1.3	1.4	2.0	2.4	2.7	2.9	**4.3**	48.5%	0.2%
Singapore	–	–	–	–	–	–	–	–	–	–	**–**	–	–
South Korea	24.4	24.5	23.6	25.9	26.7	28.1	32.2	34.8	36.1	38.2	**42.9**	12.3%	2.0%
Taiwan	11.2	12.2	14.3	15.6	16.6	17.1	19.4	21.9	23.8	24.9	**28.9**	15.8%	1.3%
Thailand	3.7	4.5	4.8	5.4	6.1	7.1	8.7	8.7	7.3	7.9	**8.4**	6.0%	0.4%
Other Asia Pacific	58.2	59.7	60.5	61.8	61.5	62.0	61.9	59.3	56.6	53.1	**53.6**	1.0%	2.4%
Total Asia Pacific	868.3	882.5	907.4	937.8	985.4	1034.8	1102.1	1085.5	1053.1	950.3	**947.2**	–0.3%	43.4%
TOTAL WORLD	**2270.3**	**2224.5**	**2211.3**	**2206.1**	**2224.4**	**2258.3**	**2341.6**	**2326.8**	**2281.1**	**2159.9**	**2186.0**	**1.2%**	**100.0%**
of which: OECD	1088.5	1067.0	1043.4	1033.8	1037.2	1043.5	1076.5	1084.8	1081.9	1070.2	**1106.5**	3.4%	50.6%
European Union 15	294.7	281.0	260.7	238.9	235.4	231.7	225.4	215.4	216.0	203.5	**209.6**	3.0%	9.6%
Other EMEs‡	827.0	839.0	861.7	895.4	941.8	987.3	1051.8	1033.7	999.6	890.8	**874.4**	–1.9%	40.0%

*Commercial solid fuels only, i.e. bituminous coal and anthracite (hard coal), and lignite and brown (sub-bituminous) coal.

†Less than 0.05.

‡Excludes Central Europe and Former Soviet Union.

the 1990 figure. Some year-by-year details for certain countries are given in Table 4.6. There have been significant reductions in Europe and the former Soviet Union but notable increases in North America and Asia-Pacific. The situation over the 11-year period from 1990 is illustrated in Fig. 4.4.

Production exceeded consumption in North America, illustrating the status of Canada and the USA as exporters of coal. But in both Europe and Asia-Pacific consumption exceeded production so as to create the need for coal imports.

The People's Republic of China is expected to have the highest growth in electricity-related coal demand at more than 4% annually. In 2020, China is projected to account for nearly one-third of the world's coal consumption for electricity generation, up from 17% in 1996. China has been the leading consumer of coal since 1982, followed by the USA. India's coal consumption is also expected to grow strongly, along with its consumption of natural gas. In the USA, coal use in the electricity sector is projected to increase by about 1% per year between 1996 and 2020.

During the 1980s, Australia became the leading coal exporter in the world, primarily by meeting increased demand for steam coal in Asia. Some growth in exports of coking coal also occurred, however, as countries such as Japan began using some of Australia's semi-soft or weak coking coals in their coke oven blends. As a result, imports of hard coking coals from other countries, including the USA, were displaced. Australia's share of total world coal trade, which increased from 17% in 1980 to 33% in 1997, is projected to reach 38% in 2020 [6]. Australia should continue as the major exporter to Asia, continuing to meet approximately one-half of the region's total coal import demand.

For the nations of Western Europe, future coal consumption is expected to decline. Western European countries are relying on increasingly available natural gas supplies for future growth in electricity production. The elimination of subsidies in the UK was largely responsible for a 50% drop in the nation's coal production between 1989 and 1997 and a greatly reduced role for coal in electricity generation.

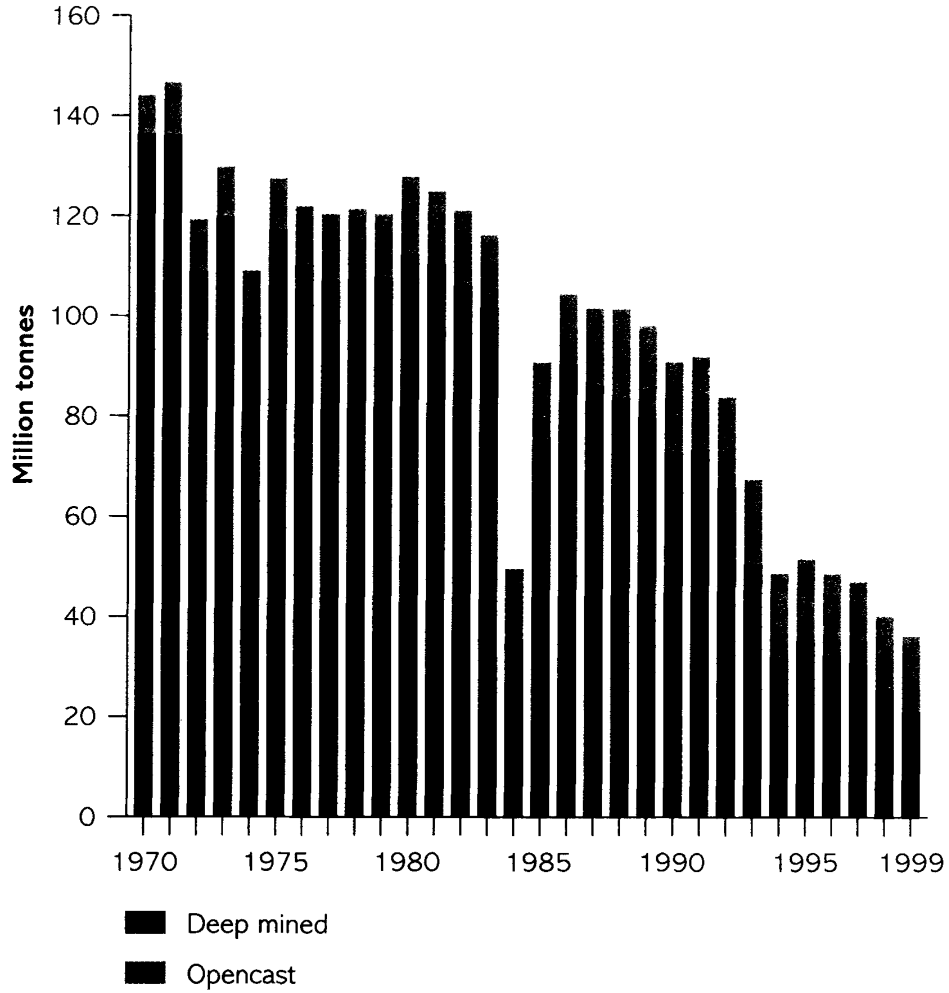
In 1997, the leading suppliers of imported coal to Europe were the USA (24%), South Africa (21%) and South America (15%). Over the near future period, low-cost coal from South America is projected to meet an increasing share of European coal import demand, displacing some coal from such higher cost suppliers as the USA and Poland.

With the exception of Germany, coal imports to Western Europe are not expected to increase to compensate for reductions in indigenous coal production. Rather, increased use of natural gas, renewable energy and nuclear power (primarily in France) is expected to fill the gap in energy supply left by the continuing reductions in the region's indigenous coal production [6].

4.2.4. *UK coal production and consumption*

UK coal production in the past 30 years is illustrated by the bar chart of Fig. 4.5 [8]. Further specific numerical information is given in Table 4.7. Coal production was 16% lower in 2000 than in 1999, with deep-mined production falling by 18%, while open-cast production fell by 12%. Coal production in 2000 was less than 24% of the level in 1980 and only 34% of the level in 1990.

The data in Table 4.8 shows that most UK coal is now used for electricity generation. Electricity generator stations (i.e. power stations) accounted for 78% of coal consumption in 2000 compared with 78% in 1990, 73% in 1980 and 49% in 1970. Coal consumption declined more sharply during the 1990s; over the last nine years at an annual rate of 7% compared with 1.5% per year over the previous 20 years. Most of the decline resulted from privatisation in the electricity sector, which led



Note: The low level of production in 1984 is a result of the miners' strike.

Source: Department of Trade and Industry.

Fig. 4.5. UK coal production, 1970–1999 [8].

Table 4.7. UK coal production [4].

Million tonnes

	1970	1980	1990	1998	1999	2000
Deep mined	136.7	112.4	72.9	25.5	20.9	17.2
Opencast	7.9	15.8	18.1	14.5	15.3	13.4
Total (including slurry)	147.2	130.1	92.8	41.2	37.1	31.2

Table 4.8. UK coal consumption, 1970–2000 [4].

Million tonnes

	1970	1980	1990	1998	1999	2000
Power stations	77.2	89.6	84.0	48.5	41.1	46.1
Domestic	20.2	8.9	4.2	2.4	2.5	1.9
Industry	19.6	7.9	6.3	2.5	2.7	1.4
Services	4.2	1.8	1.2	0.4	0.4	0.3
Other energy industries	35.7	15.3	12.5	9.4	9.1	9.2
Total consumption	156.9	123.5	108.3	63.1	55.7	59.0

to a rapid increase in gas-fired generation at the expense of coal. Substantial improvements have been made in the country's mining operations in recent years, with average labour productivity rising from less than 1000 tons per miner-year in 1989 to 2600 tons per miner-year in 1996 [9].

Despite productivity improvements and domestic production costs that are approaching parity with imported coal, British coal producers continue to face an uncertain future. Many coal contracts between producers and utilities negotiated before the privatisation of the coal industry in 1994 expired at the end of March 1998. In late 1997, initial negotiations on the renewal of the contracts indicated a strong preference among British utilities to switch from coal to natural gas. The potential negative impacts on the British coal industry and mining jobs prompted the issuance of a temporary moratorium on the construction of new gas-fired generating plants by the British government. In addition, Britain's energy minister requested an analysis of the nation's power industry to evaluate how the issues of fuel diversity and security of supply should be considered in the approval process for new power projects.

The study — the Energy Review White Paper — was completed by the UK's Department of Trade and Industry in October 1998 [10]. The report considered issues related not only to the diversity and security of energy supply but also to the design, operation and structure of the electricity market. In response to the study's findings, the British government has initiated a programme of reforms in the electricity market intended to create a more competitive environment — one in which existing coal-fired capacity will be able to compete more effectively with generation from new gas-fired plants [6].

Since 1990 the UK's domestic sector has accounted for less than 5% of the total coal consumption, which is an indication of the growth in popularity of natural-gas-fired heating systems. It is seen in Table 4.8 that the domestic sector now consumes more coal than the (non-energy industry) industrial sector. The difference between the total production and consumption coal figures, in Tables 4.7 and 4.8 respectively, shows that the UK imported $(59.0 - 31.2) = 27.8$ Mtonnes of coal in 2000, which is 47.1% of the total coal consumption.

The price of European coal, Table 4.9, has been more expensive than surface-mined American coal over most of the period since 1988. In 1999 the prices were nearing parity but during 2000 European coal again became significantly more expensive than American coal. This compares with the price of Japanese coal, which has steadily reduced since 1990.

4.2.5. *US coal production and consumption*

The USA contributed 26.7% of the world total coal production in 2000, Table 4.3, and accounted for 25.8% of the world consumption, Table 4.6. Both production and consumption increased over the 11-year period since 1990 [5]. Coal continues to be the most commonly used fuel for electricity generation, illustrated in the bar chart of Fig. 4.6 [11], but electricity producers are now (2002) increasingly turning to natural gas as the fuel source for new generation [12]. Coal deposits are widespread throughout the USA, Fig. 4.7, and active mining, mainly surface mining, takes place

Table 4.9. International coal prices, 1987–2000 [5].

Prices US dollars per tonne	Marker Price (basis Northwest Europe)*	Price of US coal receipts at steam-electric utility plants	Japan coking coal import cif price	Japan steam coal import cif price
1987	31.30	35.09	53.44	41.28
1988	39.94	33.77	55.06	42.47
1989	42.08	33.21	58.68	48.86
1990	43.48	33.57	60.54	50.81
1991	42.80	33.10	60.45	50.30
1992	38.53	32.35	57.82	48.45
1993	33.68	31.51	55.26	45.71
1994	37.18	30.88	51.77	43.66
1995	44.50	29.78	54.47	47.58
1996	41.25	29.16	56.68	49.54
1997	38.92	28.83	55.51	45.53
1998	32.00	28.26	50.76	40.51
1999	28.79	27.45	42.83	35.74
2000	36.03	27.07	39.69	34.58

*Source of Marker Price: McCloskey Coal Information Service.
Note: cif = cost + insurance + freight (average prices).

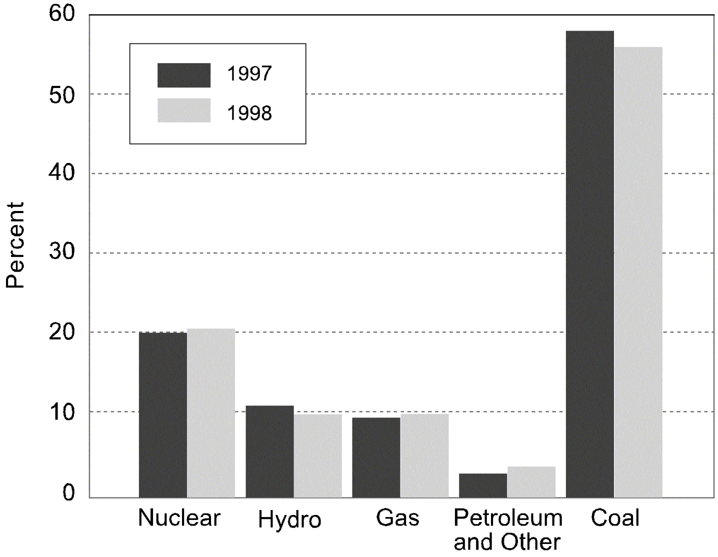


Fig. 4.6. Energy sources for the US electricity generation, 1997.

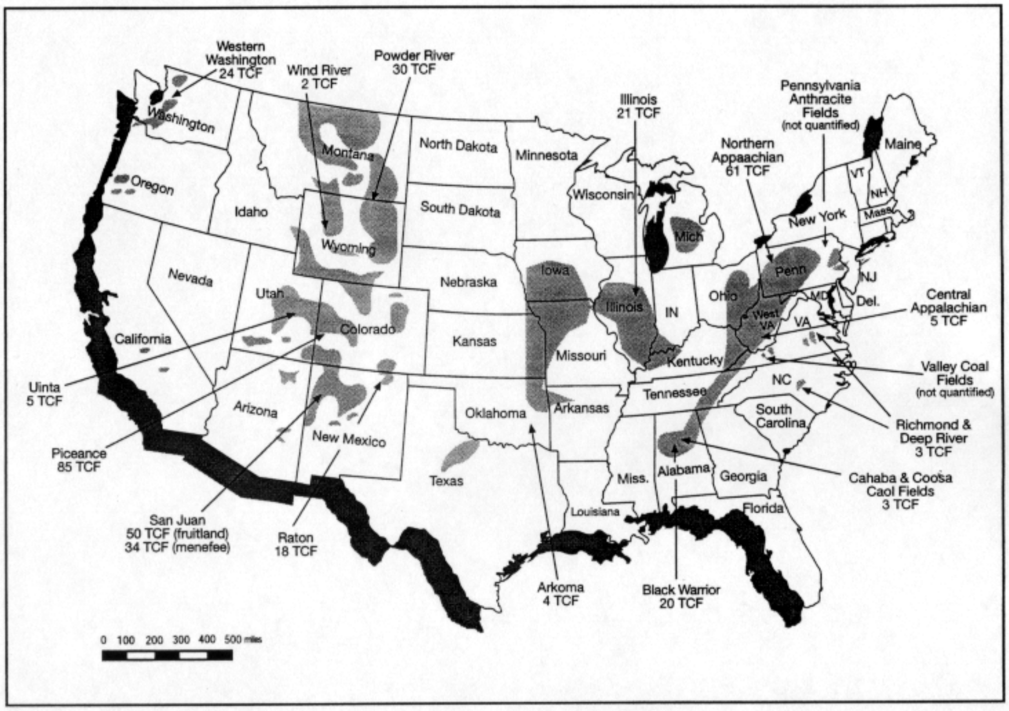

Western Washington 24 TCF
Wind River 2 TCF
Powder River 30 TCF
Illinois 21 TCF
Pennsylvania Anthracite Fields (not quantified)
Northern Appalachian 61 TCF
Washington
Oregon
Idaho
Montana
Wyoming
North Dakota
South Dakota
Minnesota
Wisconsin
Mich
New York
Maine
VT
NH
Mass
Penn
NJ
Del.
MD
Nevada
Utah
Colorado
Nebraska
Iowa
Illinois
IN
Ohio
West VA
VA
Central Appalachian 5 TCF
California
Kansas
Missouri
Kentucky
Valley Coal Fields (not quantified)
Uinta 5 TCF
Arizona
New Mexico
Oklahoma
Arkansas
Tennessee
NC
South Carolina
Richmond & Deep River 3 TCF
Piceance 85 TCF
Texas
Miss.
Alabama
Georgia
Cahaba & Coosa Caol Fields 3 TCF
Louisiana
Florida
San Juan 50 TCF (fruitland) 34 TCF (menefee)
Raton 18 TCF
Arkoma 4 TCF
Black Warrior 20 TCF
0 100 200 300 400 500 miles

Fig. 4.7. Principal US coal basins and estimated in-place coal-bed methane resources.

in about 20 states [13]. The use of coal deposits as sources of coal-bed methane — a form of natural gas — is discussed in Chapter 6.

Most of the coal consumed in the USA is used for electricity generation. Over the period 1989–1999 this proportion increased from about 85% to about 90% [11].

Other coal-producing countries, including Australia, South Africa, Colombia and Venezuela, have increased production and by aggressive pricing, coupled with favourable currency exchange rates, have achieved a growing share of traditional US export markets such as the European countries ltaly, Portugal, Spain and the UK. In addition, the competition has gained footholds within the USA. These factors have tended to cap the expansion of markets for US coal and placed strong competitive pressures among domestic producers to keep coal prices low relative to other fuels, in order to maintain existing sales quantities and market share. Concerns related to the ultimate impacts of the Kyoto Protocol and subsequent measures regarding greenhouse gases also loom over future decisions that will affect coal use [11].

In 2001 the USA announced that because of fears of economic recession it would not accept the Kyoto Protocol in its present form.

4.3. Coal Transportation

4.3.1. *Surface transportation*

In Europe and North America the common method of transporting coal is by rail. The great rivers of the USA are used as waterways to transport convoys of coal-laden barges often hundreds of miles, and about 20% of US coal is shipped in that way [14]. As in Europe, however, more than one-half the coal travels by rail. Barge transportation is cheaper than rail but is limited by the geography of the waterways and the sizes of river and canal locks. Transporting coal by road is several times more expensive than the use of rail.

In Britain, the transportation of coal is part of a complex, interactive energy-related process. The transportation of coal is, by far, the largest freight section operation of the railway system and its biggest revenue earner. There are urgent needs to limit road traffic and also to keep the railway system economically viable. But the amount of home-produced coal is declining and traditional coal-rail routes have been abandoned in favour of routes needed for imported coal, from the seaports.

It would be an obvious advantage to build electricity generation stations nearer to the supplies of coal. A successful example of this in the UK is the Drax power stations, rated at 2000 $\mathrm{MW_e}$, built in the Selby, Yorkshire coalfield.

4.3.2. *Coal slurry pipelines*

It is technically feasible to pulverise coal and to mix it, in equal amounts, with water to form a slurry. This can be transported to the user site by pipeline. At the user location the coal particles can be extracted from the slurry by centrifuges creating a pulverised fuel that is ideal for big boilers [15]. An 8-inch diameter pipeline for slurry was operational in London in 1914. Existing pipelines operate over the distance range 10–300 miles. Operation of a slurry pipeline depends on the availability of the necessary amount of water. There are cost and efficiency advantages to slurry pipelines compared with the rail transportation of coal.

The long distance slurry pipeline is a reality in the USA, where a 273-mile pipeline carries 5 million tons of coal annually, through an 18-inch pipe, from Arizona to southwestern Nevada. This is equivalent to the rail transportation of about 150 rail freight cars per day. In the UK, the widespread use of coal slurry pipeline would reduce the delivered cost of coal but would also jeopardise the income of the railway companies. A typical UK pipeline distance would need to be of the order of tens of miles rather than hundreds of miles.

4.4. Emissions and Effluents from Coal

In Western Europe and North America most of the coal consumption is now used for generating electricity. Large power stations burn pulverised coal in a suspension of fine particles. A 1000 $\mathrm{MW_e}$ coal-fired plant burns about 2.5 million tons of coal and generates roughly 6.5 billion kWh of electrical energy per year [1].

4.4.1. *Open coal fires*

Until the 1950s coal was the prime domestic and industrial fuel in the UK and was mostly burned on open fires. The smoke and gaseous effluent from these millions of fires was expelled directly into the atmosphere above residential areas. Some degree of effluent cleansing or filtration was carried out by some industries, including the electricity-generating industry, but the overall effect of open-fire coal burning, mostly residential, was massive air pollution. This was evidenced in the smoke blackening of building stone and brick and in the incidence of thick fogs in the industrial cities. A great fog in London in 1954 was a mixture of natural fog and man-made smoke and was called "smog". This lasted several days, brought transportation to a standstill and is thought to have been directly responsible for hundreds of accelerated deaths due to lung diseases [16].

Apart from the domestic inconvenience, the use of coal-burning open fires or coke-burning stoves is dirty, unhealthy and grossly inefficient. Most of the heat goes up the chimney and is wasted. The number of victims, including fatalities, of lung diseases created by or compounded by 200 years of open coal fires cannot be calculated but is probably enormous in the UK alone. A succession of legislation, the "Clean Air Acts", has largely banned open-fire coal burning in UK cities, which are now described as "smokeless".

4.4.2. *Effluents due to coal burning*

The three main pollutants from coal-burning plant flue gases are sulphur dioxide and nitrogen dioxide which produce "acid rain", plus particulates.

4.4.2.1. *Sulphur oxides*

The most important pollutants released by coal burning are sulphur products. "Inorganic" sulphur (sometimes called "mineral" sulphur) is physically distinct from but attached to the coal and can be largely removed by washing prior to combustion. "Organic" sulphur is chemically combined with the coal material and cannot be washed out. Emissions of sulphur dioxide (SO_2) are measured in terms of pounds (or kilogrammes) per million BTU burned.

Sulphur may be removed from the combustion gases by chemical "scrubbing". The sulphur-oxide-laden exhaust gases are brought into contact with a scrubbing agent, such as lime or limestone, to produce a chemical reaction that removes the sulphur. The stream of effluent from the absorbent scrubbers has its water evaporated off, producing a sludge that has to be disposed of as solid waste. For example, a unit burning 2% sulphur coal produces about 200 lb of sludge (dry weight) per ton of coal burned. A power plant of (say) 500 MW_e would create a 560-acre sludge disposal area 40 ft deep, over its lifetime [1]. More modern scrubbing agents such as sodium or recyclable metal hydroxides neutralise the sulphur oxides and also reduce the scaling of the flue pipes.

4.4.2.2. *Nitrogen oxides*

During the combustion of coal, nitrogen is drawn both from the coal and from the air in which it burns. Nitrogen oxide formation depends on the flame temperature, the time of combustion, the excess air present and the rate of cooling. To lower nitrogen oxide emissions it is necessary to modify the combustion processes. Design arrangements are effective if they involve lower combustion temperatures, restrictions of air intake, recirculation of flue gases and injection of water into the fire-box [1]. Motor vehicle exhaust gases are a bigger source of nitrogen oxides than power station flue gases in the UK. For this reason there is now UK legislation requiring all new cars to be fitted with exhaust gas filters. In the USA about one-half the nitrous oxide emissions in 1999 were due to the nitrogen fertilisation of soils in the agricultural sector [17].

Acid precipitation or "acid rain" is caused by sulphur dioxide and nitrogen oxides mixing chemically with water vapour in the atmosphere. These emissions are mainly derived from coal and oil combustion, which is dispersed through tall chimneys to prevent high concentrations at ground level. Due to air motion, increases in the acidity of the local rainfall may occur hundreds of miles downwind from the site of the pollution. The emitted gases may be oxidised to sulphates and other chemical changes may occur, influenced by varying conditions of temperature, humidity and solar irradiation [1]. Also, the chemical nature of the gases may be affected by substances originating in the territories over which they travel.

There is evidence that pollution from power plants in the UK is blown from west to east and deposits, in the form of acid rain, onto locations in Norway and Sweden. The rain acidity can accelerate the leaching of ground toxic materials such as aluminium and mercury into water courses. There is also evidence of damage to forests and fish stocks, especially in areas with acid soils [2].

The problem of acid rain has to be approached on the basis of international collaboration. Technical aspects of the acid rain problem can only be tackled at source. There is no form of prevention once the acidity is created.

4.4.2.3. *Particulates*

Flue gases from coal-burning operations contain small particles of solid materials, mainly carbon. There is a range of particle sizes down to less than 1 mm, and the suspensions of smaller particles can be ingested or inhaled by respiration. Particulates may travel hundreds of miles from their point of origin, accompanying emissions of gas from the same source. The chemical nature of particulates can change in transit. Both increases and decreases of toxicity have been noted [18]. Also, during transit, the emitted gases may form aerosols (fine suspensions) through condensation and coagulation. These may react with other fine suspensions, leading to increases of particulate size with changed physiological effects, if ingested or inhaled into human bodies.

In order to satisfy stringent environmental regulations, chimney effluents are controlled by one or more of four filtration processes: mechanical collectors, electrostatic precipitators, ubbers and fabric baghouses. All the methods are more effective in capturing the larger size particles. Sometimes two types are used in series, with a cheap and relatively inefficient first stage acting to reduce the loading on a more efficient and more expensive second stage.

Mechanical collectors use gravity, inertia or centrifugal forces to separate (mainly) heavier particles from the gas. The simplest form consists of enlarged chambers in the gas stream which slows down the flow rate, enabling the heavier particles to settle. Other methods use centrifugal swirling of the gases, which causes the heavier particles to travel to the outer walls and drop to the bottom of the chamber [1].

Electrostatic precipitators are used by the UK electricity generation industry. The flue gases are passed between a high-voltage electrode and a grounded collection plate. The ionised particles move towards the grounded plate, where they are collected and removed. As much as 99.9% (by weight) of the particles can be removed but the precipitation works best on the heavier particles. With low sulphur, coals the particles tend to be electrically more resistive. This makes electrostatic site precipitation more expensive because the precipitator may then need to operate in a hotter part of the flue gas, where the higher temperature reduces the resistivity of the carbon particles. Alternatively, bigger precipitators may be required.

Wet scrubbers are sometimes used to wash solid particles from the gas stream using water. This is essentially a physical scrubbing process that is different from the chemical scrubbing of sulphur oxides, described in Sec. 4.4.2.1 above.

For the filtration of the finer particles, the most effective method is to use fabric filter baghouses. The flue gas is forced through fine filters, effecting filtration but causing a pressure drop. This increases the operating costs. The method is widely used for general purpose industrial applications. High temperature, corrosive gases due to coal combustion in power utility boilers pose particular problems for filter methods [1].

4.4.2.4. *Carbon dioxide*

The burning of coal releases carbon dioxide (CO_2) gas and thereby contributes to the possibility of global warming due to the accumulation of so-called "greenhouse" gases. This is discussed in Sec. 2.6.7 of Chapter 2.

4.4.2.5. *Carbon dioxide emissions due to coal*

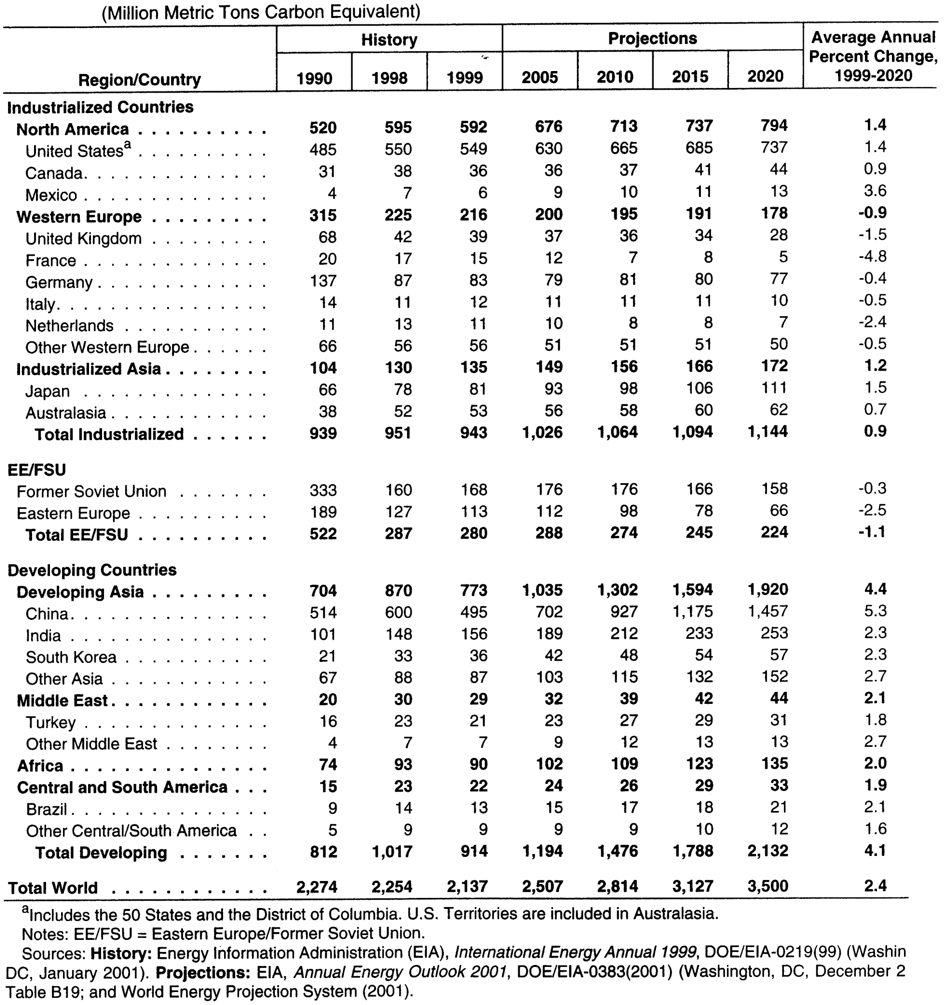
Table 4.10 gives figures for past and projected future emissions of carbon dioxide due to the use of coal. Comparable information is given in Table 5.5 of Chapter 5 for oil and in Table 6.5 of Chapter 6 for natural gas. Carbon dioxide emissions due to coal are seen to be smaller than those due to oil in the OECD countries and the Middle East but much larger in China. There is a close correlation between the amount of coal consumed, Table 4.6, and the consequent amount of carbon dioxide emitted, Table 4.10.

If the figures for carbon dioxide emissions due to coal, oil and natural gas in the three tables compared with the total primary energy use in Table 2.8 of Chapter 2, it is found that, from the viewpoint of carbon dioxide emission, natural gas is the cleanest fuel. Natural gas contributed $\frac{2164}{8752.4} = 24.7\%$ of world primary energy consumption in 2000, Table 2.3, but is projected to create $\frac{1531}{7015} = 21.8\%$ of the fossil fuel carbon dioxide emissions in 2005, Table 6.6. Oil use contributed to carbon emissions pro rata to its world consumption of 40%. Coal was relatively "dirty" in generating $\frac{2137}{6091} = 35\%$ of the total fossil fuel carbon dioxide emissions in 1999, Table 4.10, while contributing $\frac{2186}{8752.4} = 25\%$ of the world primary energy consumption, Table 2.3.

4.5. Advanced Coal Technologies

Research and development of the use of solid fuels has two main aims: to improve the efficiency of energy conversion and to reduce the adverse environmental effects.

Table 4.10. World carbon dioxide emissions from coal use by region, high economic growth case, 1990–2020 [6].



(Million Metric Tons Carbon Equivalent)

Region/Country	History			Projections				Average Annual Percent Change, 1999-2020
	1990	1998	1999	2005	2010	2015	2020	
Industrialized Countries								
North America	**520**	**595**	**592**	**676**	**713**	**737**	**794**	**1.4**
United States[a]	485	550	549	630	665	685	737	1.4
Canada	31	38	36	36	37	41	44	0.9
Mexico	4	7	6	9	10	11	13	3.6
Western Europe	**315**	**225**	**216**	**200**	**195**	**191**	**178**	**-0.9**
United Kingdom	68	42	39	37	36	34	28	-1.5
France	20	17	15	12	7	8	5	-4.8
Germany	137	87	83	79	81	80	77	-0.4
Italy	14	11	12	11	11	11	10	-0.5
Netherlands	11	13	11	10	8	8	7	-2.4
Other Western Europe	66	56	56	51	51	51	50	-0.5
Industrialized Asia	**104**	**130**	**135**	**149**	**156**	**166**	**172**	**1.2**
Japan	66	78	81	93	98	106	111	1.5
Australasia	38	52	53	56	58	60	62	0.7
Total Industrialized	**939**	**951**	**943**	**1,026**	**1,064**	**1,094**	**1,144**	**0.9**
EE/FSU								
Former Soviet Union	333	160	168	176	176	166	158	-0.3
Eastern Europe	189	127	113	112	98	78	66	-2.5
Total EE/FSU	**522**	**287**	**280**	**288**	**274**	**245**	**224**	**-1.1**
Developing Countries								
Developing Asia	**704**	**870**	**773**	**1,035**	**1,302**	**1,594**	**1,920**	**4.4**
China	514	600	495	702	927	1,175	1,457	5.3
India	101	148	156	189	212	233	253	2.3
South Korea	21	33	36	42	48	54	57	2.3
Other Asia	67	88	87	103	115	132	152	2.7
Middle East	**20**	**30**	**29**	**32**	**39**	**42**	**44**	**2.1**
Turkey	16	23	21	23	27	29	31	1.8
Other Middle East	4	7	7	9	12	13	13	2.7
Africa	**74**	**93**	**90**	**102**	**109**	**123**	**135**	**2.0**
Central and South America	**15**	**23**	**22**	**24**	**26**	**29**	**33**	**1.9**
Brazil	9	14	13	15	17	18	21	2.1
Other Central/South America	5	9	9	9	9	10	12	1.6
Total Developing	**812**	**1,017**	**914**	**1,194**	**1,476**	**1,788**	**2,132**	**4.1**
Total World	**2,274**	**2,254**	**2,137**	**2,507**	**2,814**	**3,127**	**3,500**	**2.4**

[a] Includes the 50 States and the District of Columbia. U.S. Territories are included in Australasia.

Notes: EE/FSU = Eastern Europe/Former Soviet Union.

Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 1999*, DOE/EIA-0219(99) (Washin DC, January 2001). **Projections:** EIA, *Annual Energy Outlook 2001*, DOE/EIA-0383(2001) (Washington, DC, December 2 Table B19; and World Energy Projection System (2001).

4.5.1. *Fluidised-bed combustion*

Fluidisation is a technology for causing small solid particles to behave as if they were a liquid. Coal is burned in a mixture with limestone (to absorb sulphur) suspended in a stream of combustion air rising from beneath the heated bed, Fig. 4.8. Optimum combustion and heat transfer to the heating coils requires appropriate design of the air flow and coal configuration. Compared with the combustion of pulverised coal, the sulphur dioxide is largely absorbed within the high pressure gas circuit and nitrogen oxide emissions are substantially reduced due to lower working temperatures. The combustion techniques can also utilise lower grades of coal

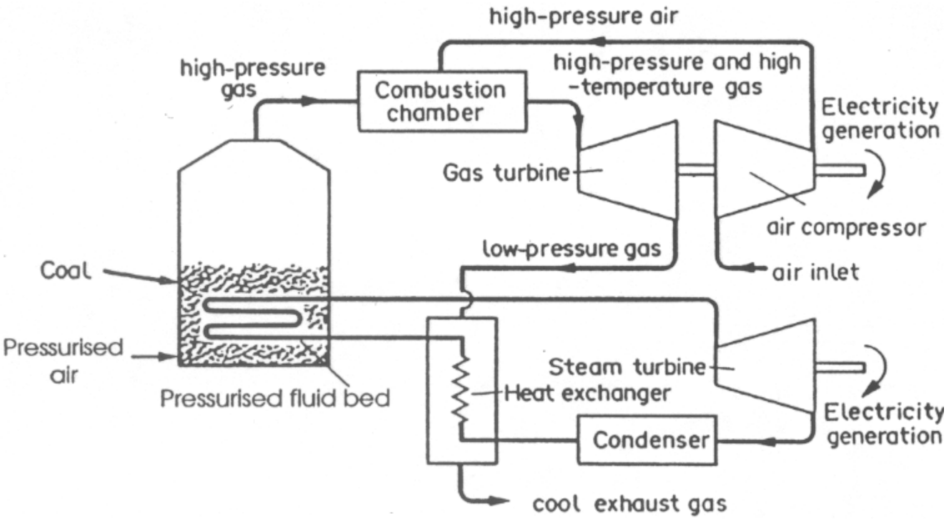

high-pressure air
high-pressure gas
Combustion chamber
high-pressure and high -temperature gas
Electricity generation
Gas turbine
air compressor
low-pressure gas
air inlet
Coal
Pressurised air
Pressurised fluid bed
Steam turbine
Heat exchanger
Condenser
Electricity generation
cool exhaust gas

Fig. 4.8. Combined-cycle integrated gas and steam turbines [2].

[19]. Pressurised fluidised-bed systems are more efficient and result in lower levels of emissions than atmospheric level fluidised-bed systems.

4.5.2. *Combined-cycle generation*

Combustion systems that combine a gas-turbine-driven generator with a separate steam-turbine-driven generator are called "combined-cycle" systems. Figure 4.8 shows an integrated system where a fluidised-bed heater simultaneously heats the fluid in the hot water/steam loop feeding the steam turbine and also heats the coal gas feeding the gas turbine (the hotter the gas, the more efficient the gas turbine operation). Exhaust heat from the gas turbine, in the form of low-pressure gas, is used to reinforce the heat transferred from the fluidised-bed steam circuit. This is inherently the most efficient power cycle available and is gradually overtaking steam-only generation. A steam-only station, most of which are coal-fired, has a full-load efficiency of about 30%. Combined-cycle plants now (2002) have full-load efficiencies greater than 50%, although the fuel costs are greater. The modern practice is to combine a coal-fired steam plant with a natural gas system, Fig. 4.9 [20]. It is also possible to combine the steam cycle with heat energy from nuclear, wind or solar generation systems [21]. A relevant solar system is described in Sec. 11.5.3 of Chapter 11.

In 1999 the USA had 199 combined-cycle units with a capacity of 16,817 MW, which was only 2% of the total electric power capability of 785,990 MW [22]. It is planned to add an additional 71 combined-cycle units, with nameplate capacity of 17,288 MW, through the year 2004. In the UK the use of gas turbine combined-cycle stations increased from zero in 1973 to 11.6% of the total generation in 1994.

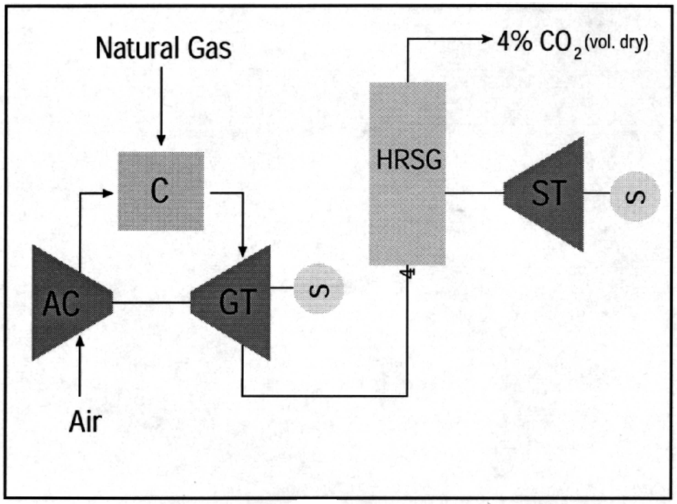


Fig. 4.9. A schematic of the gas turbine combined-cycle power generation system [20].

AC = air conditioner
HRSG = heat recovery steam generator
GT = gas turbine
ST = steam turbine

The use of natural gas is now increasing to the extent that one-third of the total UK electricity generation is expected to come from combined-cycle plants within the next few years.

The chief advantage of natural-gas-steam combined-cycle generation, compared with steam only, is the great increase of overall efficiency. In addition, the use of combined-cycle systems results in a much lower coal use and a significant reduction of greenhouse gases. There are big reductions of sulphur dioxide, nitrogen oxides, carbon dioxide, particulates and fly ash.

It is important to note that combined-cycle operation, where two fuel sources are used, is not the same as cogeneration or combined heat and power (CHP), reported in Sec. 3.8 of Chapter 3. The two technologies are quite different, although sometimes they are incorporated on the same plant site.

4.6. Liquid Fuels from Coal

The extraction of liquid fuels from coal has been the subject of much investigation for over 100 years. Because of the low price of crude oil it is not an active process at present (2002).

Four main approaches are used:

(a) indirect liquefaction
(b) pyrolysis

(c) solvent extraction
(d) direct hydrogenation (catalytic liquefaction)

4.6.1. *Indirect liquefaction*

In this process the feed coal is completely gasified to produce a "synthesis" gas. Purification methods are then used to remove particulates and sulphur compounds. Liquid products, usually rich in aromatic compounds ranging from gasoline to heavy oils and waxes or methanol, are obtained by high temperature and high pressure reactions in the presence of appropriate catalysts. Indirect liquefaction processes have low thermal efficiencies, of the order 40–45%.

The best-known method is the Fischer–Tropsch process, developed in Germany in the 1930s. A large scale commercial operation is the SASOL plants in South Africa, which initially produced petrochemicals and fertilisers. By the mid-1980s three plants used 30 million tonnes of coal per year to produce gasoline, diesel fuel, LNG, kerosene and other products [19].

A great advantage of indirect liquefaction, compared with the three direct methods described below, is that it does not require the heavy use of hydrogen in refining the heavier liquids. This may be a significant cost advantage.

4.6.2. *Pyrolysis*

In pyrolysis the coal is heated in the absence of air or oxygen, which breaks down the coal molecules to form ethane and methane, leaving a remnant called "char". Hydrogenation can be achieved using the intrinsic hydrogen from the coal or by applying a stream of hydrogen which improves the liquid yield. Crude benzoil refining using pyrolysis began about a hundred years ago. Although the thermal efficiency can exceed 80% the overall production cost is not at present (2002) competitive with natural crude oil.

4.6.3. *Solvent extraction*

In the solvent extraction processes, finely crushed and dried coal is treated with a hot, liquid, hydrogenated solvent oil, derived from coal.

The hydrogenation reaction is catalysed to some extent by inorganic substances in the coal. After processing it is possible to generate hydrogen plus a range of hydrocarbon products that can be upgraded to gasoline or diesel fuel. One of the technical problems in the solvent extraction is how to separate the undigested coal and ash from the liquid products [1]. The heavier residual oils can be recycled as the solvent oil [2, 23]. Thermal efficiencies of 60–65% have been realised in experimental process reactors. Solvent extraction methods can typically yield 2.5–3 barrels of liquid per ton of coal.

4.6.4. *Direct hydrogenation (catalytic liquefaction)*

With the direct hydrogenation process a reducing gas such as high-purity hydrogen at high temperature and pressure reacts with the coal in the presence of a catalyst. Some catalytic processes use a suspension of coal in heavy oil and pass this over a catalyst bed to avoid intimate contact between the coal and the catalyst. This eliminates the need for the large-scale replacement of catalysts that would arise where the catalyst is in direct contact with the coal. The coal products are mainly aromatic. In the UK the Imperial Chemical Industries plant at Billingham had a capacity of 100,000 tonnes per annum of liquid fuel in the 1930s.

The commercial viability of extracting liquid fuel from coal depends on the supply and price of oil. At the present time (2002) the price of natural crude oil is too low for synthetic liquid fuels from coal to represent serious competition. It is not clear if the use of coal liquids is environmentally "cleaner" than the burning of coal itself. The combustion processes in coal liquefaction may be cleaner but the overall processes themselves may represent a greater industrial hazard because of the distillation of impurities. There is a concentration of polycyclic organic matter in the heavy fractions of coal liquids [1].

4.7. Problems and Review Questions

4.1. Use the information in Tables 4.3 and 4.6 to list the world's ten largest producers and consumers of coal at the present time.
4.2. Which countries of the world were big exporters or importers of coal during the year 2000?
4.3. In which countries of the world did coal production (a) increase, (b) decrease most significantly between 1995 and 2000?
4.4. In which countries of the world did the consumption of coal (a) increase, (b) decrease most significantly between 1995 and 2000?
4.5. Use the data of Tables 4.7 and 4.8 to discuss the figures for coal mined and coal used in the UK from 1980 to 1999.
4.6. Use the data of Tables 4.3 and 4.6 to discuss the figures for coal production and consumption in the USA between 1990 and 2000.
4.7. Compare the UK coal production since 1970 due to (a) deep mining, (b) open-cast (surface) mining.
4.8. How did the proportion of coal used in the UK domestic sector change from 1970 onwards? What were the reasons for the change?
4.9. How has the proportion of coal used in electricity generation in the UK changed since 1980?
4.10. Despite high labour costs, the price of US coal was lower than those of European and Japanese coal during the 1990s. Why was this so?
4.11. The USA accounts for more than one quarter of world coal consumption. What is the coal used for?

4.12. What are the (a) advantages and (b) disadvantages of burning domestic coal in open fire places?
4.13. What are the (a) advantages and (b) disadvantages of using coal as the prime fuel for electricity generation?
4.14. How is coal transported from the pit-head to the user sites?
4.15. Explain the nature and purpose of coal slurries.
4.16. What are the main pollutants due to coal burning?
4.17. Explain what is meant by the term "acid rain". How does this occur and what are its effects?
4.18. Briefly describe the nature of the electrostatic precipitation operations used in power utility boiler emission systems.
4.19. Briefly explain four methods of obtaining synthetic liquid fuels from coal. Why are such methods not widely used to supplement the world's dwindling oil supplies?
4.20. In the USA, as in Western Europe, the coal mining industry has passed through deep recession in the past 20 years. Why is this so?

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CHAPTER 5

PETROLEUM

5.1. Introduction

In the energy industries the word “petroleum” is usually understood to include both “oil” and “natural gas”. But in this chapter that word refers only to oil.

It is believed that oil was formed principally from the remains of marine plants buried in sedimentary rocks. The earliest oils have been found in Precambrian rock formations (i.e. more than 1000 million years old) and predate the formation of coal by hundreds of millions of years — long before vegetation appeared on the land masses [1, 2]. Because of the marine origin, oil deposits are widely distributed on the earth. They frequently occur in present coastal areas, beneath continental shelves and under inland areas that were once ocean beds. Large accumulations occur in lacustrine rocks (i.e. rocks associated with lakes or wetlands). After extraction from sediments, naturally occurring liquid oil is known as “crude oil”. It then needs to be refined for most of its applications.

Most of the world’s oilfields extend only a few square miles, although some of the largest fields cover several hundred square miles. Some deposits contain only natural gas and these are often found at great depths. Where a deposit contains oil it also contains natural gas, in layers above the oil or dissolved into the oil (like carbon dioxide gas dissolved into lemonade to give it “fizz”). For high pressure deposits the oil and gas, combined in the reservoir as “condensate”, may separate naturally before they reach the surface. This separation can be reinforced by pressurised recovery techniques. Modern oil exploration is now very sophisticated at predicting the locations of oil deposits (occurrences), using remote sensing and geophysical techniques, but such predictions can only be confirmed by drilling. Not all oil well drilling strikes oil. In spite of the reasonable scientific expectation the success ratio is only about 1 in 5. Drilling and exploration costs for new well sites constitute over 40% of oil company capital expenditures.

When an oilfield is successfully located, not all of the oil is recoverable. If the natural oil pressure in the deposit is sufficient to drive the liquid crude oil upwards to the ground or ocean bed surface, then about 30% of the oil reservoir can be economically recovered (primary recovery). If the natural pressure of an oil deposit is enhanced by injecting pressurised air or water or by reinjecting natural gas, a higher proportion of the oil deposit can be recovered but at consequent greater expense (secondary recovery). Any reinjected gas can be eventually recovered. A still greater yield can be obtained by other methods of recovery (tertiary recovery). This is one of the reasons why estimates of oil deposits (occurrences), and recoverable reserves are rather speculative and dependent on economic as well as technical considerations. The extraction of oil results in high revenue for the oil companies, compared with the extraction of natural gas only.

The general term “petroleum” is now used to cover a wide range of hydrocarbons, including natural gas. Various “cuts” of hydrocarbons include bitumen and solid paraffin waxes. Petrol (or gasoline) and diesel fuel, used as engine fuels, have to be obtained by the “refining” of crude oil.

Oil is measured by volume, but characterised by weight. A barrel of oil is 159 litres, which is 42 US gallons or 34.97 imperial gallons. In terms of weight a barrel of oil is 0.136 tonnes and has an equivalent heat energy of 5.694×10^9 J. For the large scale use of oil it is customary to use MMBL (millions barrels of oil) or the quantity million tonnes (mto). To afford a direct comparison of the energy values, other fuels such as coal or natural gas use the quantity MMBL oil equivalent or million tonnes of oil equivalent (mtoe).

The capacity of an oilfield is usually estimated in millions of barrels. For example, the Prudhoe Bay deposit in Alaska has been estimated at 12 billion (12×10^9) barrels. From British Petroleum’s offshore fields in the North Sea between Scotland and Norway the production is about a million (10^6) barrels per day. This compares with the latest (2001) figure, 1064.4 thousand million barrels or 142.1 thousand Mtonnes of proved world reserves [3, 4].

5.2. History and Development of the Petroleum Industry

Oil and its products have been used in some of the earliest civilizations, such as those of Mesopotamia (now Iraq) and Egypt (i.e. 3000–2000 BC). This was usually obtained from surface seepages. In the form of asphalt it was used for caulking boats, setting jewels into frames, preserving mummies, and for building construction and waterproofing.

Forms of light oil produced by elementary methods of distillation were used by the Arabs as incendiary weapons of war as early as the seventh century AD [5]. In the 18th century, oil produced from oil shale was used for street lighting in Modena, Italy, and for paraffin wax candles in Scotland.

Modern oil exploration in the form of the familiar drilling rig began in Pennsylvania, USA, in 1859 with Edwin L. Drake’s well, which was about 20 m deep. By the end of the 19th century there was a virtual monopoly in the USA owned by Standard Oil of New Jersey in the person of John D. Rockefeller, who became the richest man in the world. The Standard Oil industrial cartel was broken up into smaller units by US anti-trust legislation in 1911. The international oil industry was dominated by the USA, because of its vast natural resources and business acumen, until the period of the Second World War (1939–45). The great oilfields of the Middle East, particularly Saudi Arabia, now a repository of much of the world's reserves, were discovered and developed during the 1920s and 1930s by American and European explorers and engineers.

5.2.1. *The Seven Sisters* [6]

Until 1973 the production and price of crude oil were mostly controlled by seven great international companies, known in the oil trade as the "Seven Sisters". In descending order of assets, these were Exxon (USA), Royal Dutch/Shell (Netherlands/Britain), Texaco (USA), Gulf Oil (USA), Mobil (USA), British Petroleum (BP) (Britain) and Socal (now Chevron) (USA). In the UK the Exxon company operates under the trade name of "Esso". A recent (1999) merger between BP and the American Oil Company (AMOCO) and later with ARCO has moved BP/Amoco into third place in the Seven Sisters list. Exxon and Mobil joined forces recently to become the world's largest oil company.

The huge financial profits made by the Seven Sisters from Middle Eastern oil lured other American companies into the Middle Eastern market during the 1950s. Companies such as Standard Oil of Indiana (Amoco), Standard Oil of Ohio (Sohio), Continental (Conoco) and Atlantic Richfield (Arco) also became large, powerful and wealthy. Various individual business entrepreneurs, such as John Paul Getty and Harold Layfayette Hunt, operated independently to their immense profit. Armand Hammer turned Occidental into a large and profitable company. Relations between the independents and the Seven Sisters were often conducted in terms of bitter rivalry and contributed to the eventual downfall of the western oil monopoly.

Two major oil discoveries occurred in the 1960s and 1970s, both outside the Middle East. In 1959 a joint Exxon–Shell team found the giant Groningen natural gas field off-shore Holland. Also, in 1965, BP found natural gas off the coast of England and later discovered oil in the northern North Sea. Meanwhile, in 1968, one of the American independents (Arco) discovered oil in Prudhoe Bay, Alaska. For financial reasons Arco was obliged to bring in the oil giant Exxon, which soon became the dominant partner. Nine months later BP also struck oil in Alaska. The Alaskan fields proved to be massive, exceeding in size the deposits in Western Texas.

5.2.2. *European oilfields*

In 1970 BP discovered the giant Forties oilfield under the North Sea, north of Aberdeen, Scotland. One year later, in 1971, Shell/Exxon found the equally large Brent oilfield off the Shetland Islands, north of Scotland. During the 1970s and

1980s a signifcant number of large and medium-sized oil fields were discovered in the North Sea. Having been a consumer nation throughout its history, the UK was then faced with the challenges of becoming a major producer. Initially the British government was lacking in both the expertise and the will to become an oil producer. Huge areas of the sea for exploration were leased to US companies at ridiculously low rates, which excluded them as sources of UK tax revenue. By 1973 BP controlled 20% and Shell 15% of the North Sea oil but the majority was still controlled by the American sisters. It was not until seven years after the first exploration concessions that the UK parliament eventually caught up with the extent of the oil companies' bonanza [6]. A government report in 1973 was a devastating criticism of the UK civil service, in that Britain would receive a smaller share of oil revenues than other countries and that British taxes were being pre-empted by the tax demands of administrations abroad [6]. A new government, elected in 1974, passed legislation to resolve the balance in favour of the UK taxpayers.

The UK government was a significant shareholder in BP from 1914 to 1987. For example, in 1974, 48% of BP stock was held by the government, although BP was never state-owned. This asset was largely sold off by privatisation in 1987, leaving only a 1.8% shareholding. The small remainder was fully liquidated in December 1995 and raised more than £500 m [7].

5.2.3. *OPEC*

In 1960 an organisation was formed by the major oil producer countries (excluding the USA) to counter the influence of the Seven Sisters. This became known (and remains known) as the Organisation of Petroleum Exporting Countries (OPEC). The 12 OPEC countries, listed in Table 2.1 of Chapter 2, led by Saudi Arabia, contain more than 65% of the world's oil reserves. In 1973, after much dispute between the supplier countries of OPEC and the western oil companies, the OPEC suppliers acted unilaterally and suddenly increased the price of crude oil. The result was widespread disruption in the industries of North America and Western Europe. The price of oil quadrupled in a year, leading to what Western politicians described as the "oil crisis". In effect, control over the production and price of oil had passed from the historical masters to the producers. The price and production of oil are now fixed by negotiations between OPEC and the oil producers, but subject to consultation with the governments of various concerned countries. There are a number of major producers (including Russia, the USA, the UK and Norway) who are not members of OPEC.

The historical price of crude oil is shown in Fig. 5.1 [3]. Characteristics are shown for both the historical price at the time and the price adjusted to the 2000 value of the US dollar. For 100 years the price of crude oil was uniformly low — of the order of a few US dollars/barrel. This increased dramatically during the 1970s

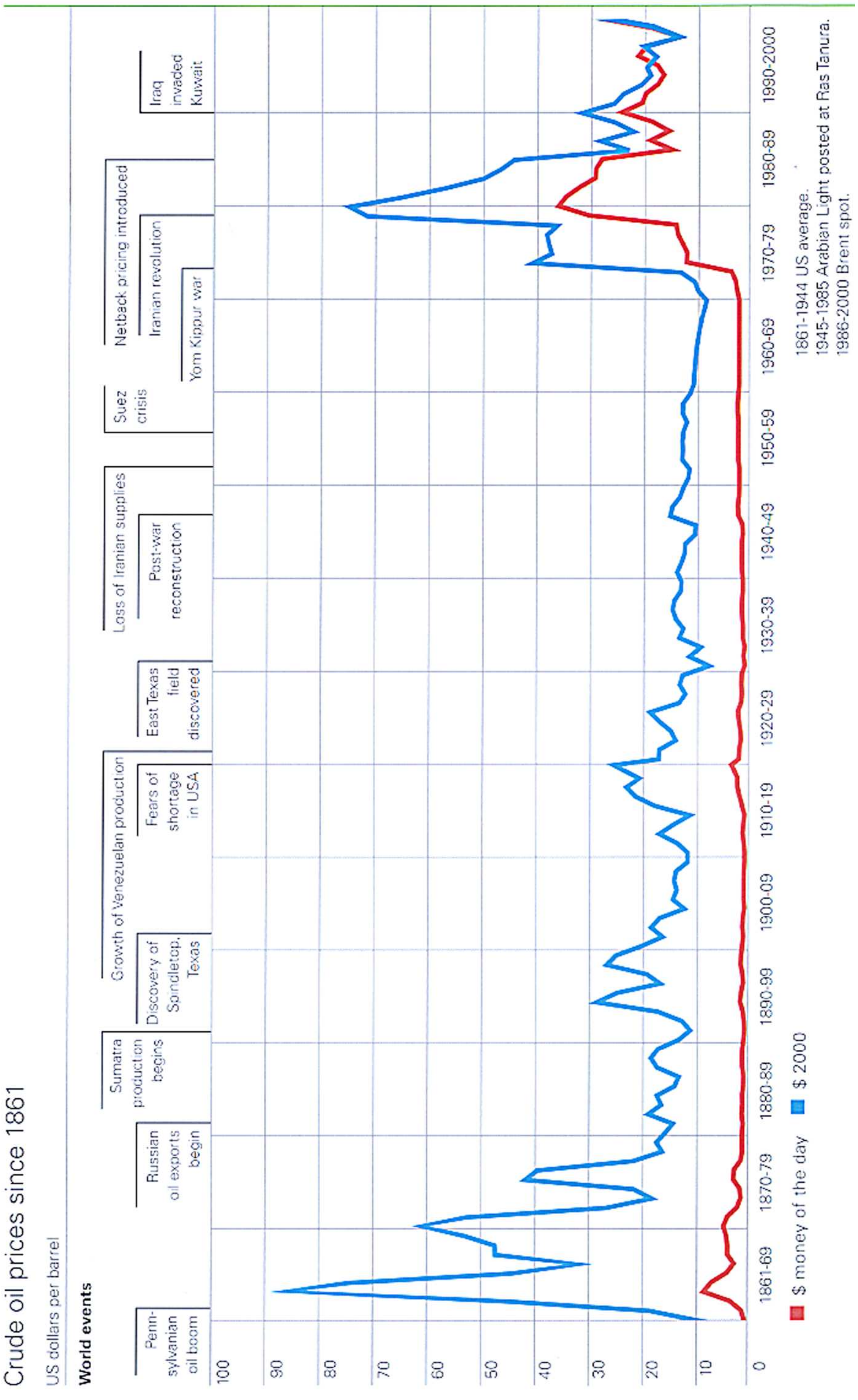
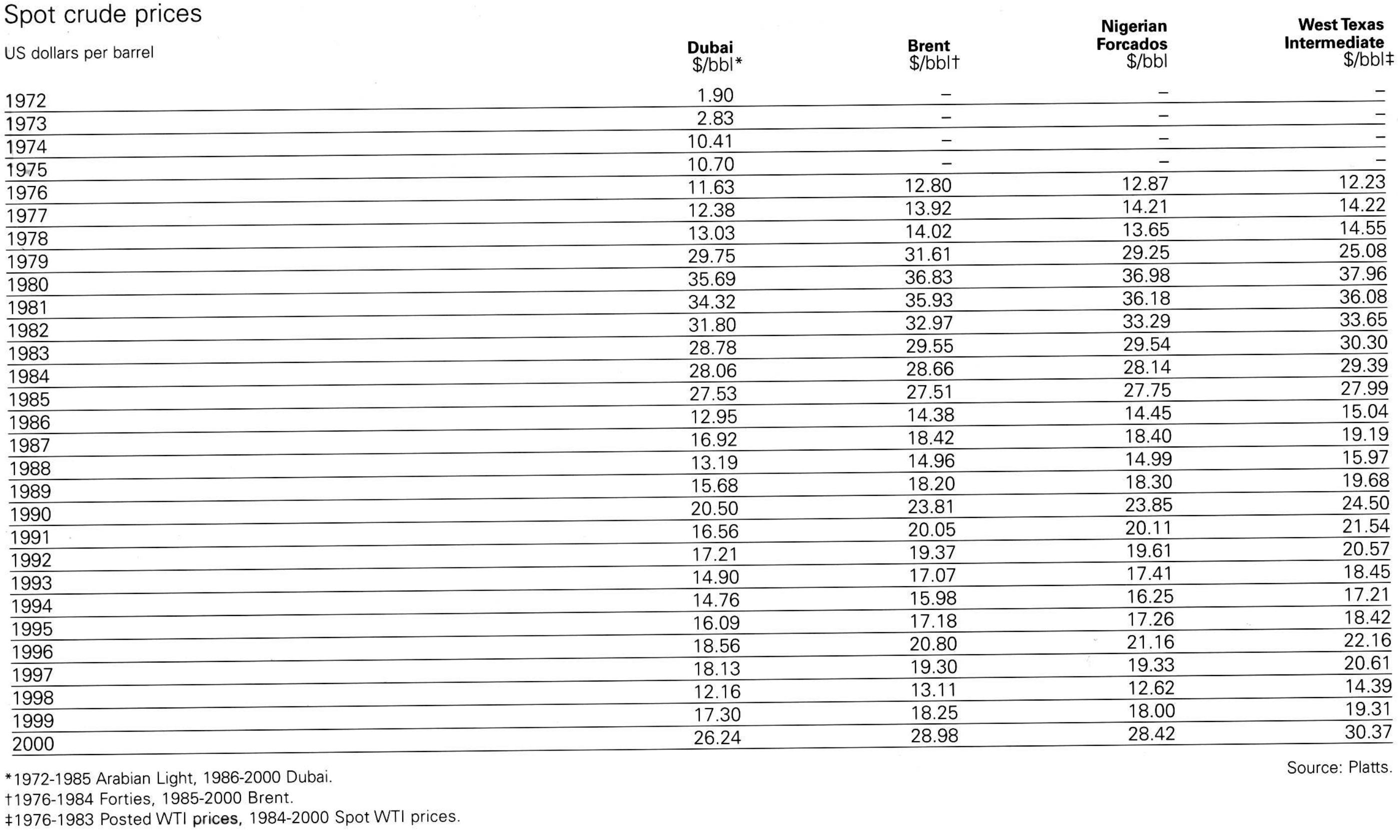


Fig. 5.1. Crude oil prices, 1861–2000 [3].

Table 5.1. Crude oil prices, 1972–2000 [3].

Dubai — Middle Eastern
Brent — North Sea
Nigerian — West African
West Texas — US



Spot crude prices

US dollars per barrel

	Dubai $/bbl*	**Brent** $/bbl†	**Nigerian Forcados** $/bbl	**West Texas Intermediate** $/bbl‡
1972	1.90	–	–	–
1973	2.83	–	–	–
1974	10.41	–	–	–
1975	10.70	–	–	–
1976	11.63	12.80	12.87	12.23
1977	12.38	13.92	14.21	14.22
1978	13.03	14.02	13.65	14.55
1979	29.75	31.61	29.25	25.08
1980	35.69	36.83	36.98	37.96
1981	34.32	35.93	36.18	36.08
1982	31.80	32.97	33.29	33.65
1983	28.78	29.55	29.54	30.30
1984	28.06	28.66	28.14	29.39
1985	27.53	27.51	27.75	27.99
1986	12.95	14.38	14.45	15.04
1987	16.92	18.42	18.40	19.19
1988	13.19	14.96	14.99	15.97
1989	15.68	18.20	18.30	19.68
1990	20.50	23.81	23.85	24.50
1991	16.56	20.05	20.11	21.54
1992	17.21	19.37	19.61	20.57
1993	14.90	17.07	17.41	18.45
1994	14.76	15.98	16.25	17.21
1995	16.09	17.18	17.26	18.42
1996	18.56	20.80	21.16	22.16
1997	18.13	19.30	19.33	20.61
1998	12.16	13.11	12.62	14.39
1999	17.30	18.25	18.00	19.31
2000	26.24	28.98	28.42	30.37

Source: Platts.

*1972-1985 Arabian Light, 1986-2000 Dubai.
†1976-1984 Forties, 1985-2000 Brent.
‡1976-1983 Posted WTI prices, 1984-2000 Spot WTI prices.

but fell again during the 1980s. Table 5.1 shows that in 2000 Middle Eastern oil rose to $26.24/barrel compared with $1.90/barrel in 1972 — a 14-fold increase. The price of oil slumped to about $18/barrel in 2001, so that the OPEC producers and some major non-OPEC producers introduced cutbacks of production to maintain the oil price.

Figure 5.1 cites certain "world events", demonstrating the volatility of the price of crude oil, linked particularly to major political events in the Middle East in the past 30 years.

5.3. World Oil Reserves

Estimates of proved oil reserves tend to be revised upwards each year as more sophisticated methods of evaluation are employed and recovery rates increase due to improved technology. The upward revisions are, however, marginal and at present are roughly keeping pace with increased oil consumption. Depletion of the world's oil reserves in 2000 was balanced by additions from new discoveries and higher recovery rates from existing fields [3]. In 2000 world oil reserves were slightly up on the 1999 figure but maintained the general level of the 1990s, Fig. 5.2 and Table 5.2. The geographical distribution of the presently known crude oil deposits is shown in Fig. 5.3, which correlates with Table 5.2 [3]. The Middle East reserves are roughly twice the combined value for the rest of the world. This is reflected in the figures for the area reserves, Fig. 5.2, and the R/P ratios in terms of years of reserve remaining, Fig. 5.4. No "official" figures are available for the old USSR but these contain large amounts of oil and natural gas. It is obvious that urgent planning is needed on the part of the western countries, especially Western Europe, in anticipation of their own oil supplies running out. Figure 5.4 shows that the world oil reserve/production (R/P) ratio in (2000) gives a figure of 40 years. Although this figure has reduced only slightly since 1990 due to revised upward reserve estimates, it would not be wise to assume that this trend will always continue. When world oil consumption, which is rising, starts to outstrip the revised reserve estimates, the years of remaining world oil reserves will inevitably decline. Only the discovery of new massive, extractable, economic crude oil deposits would cause the years of reserves to rise dramatically. Improved methods of primary recovery (see Sec. 5.1 above) and rehabitution (i.e. re-entry to oil fields that have stopped producing) is a major new way of increasing production and would increase available world reserves. Some authors would dispute the accuracy of the estimate of 40 years. Their argument is based on the assumption that political and (especially) economic factors will reduce the rate of oil usage in future years, thereby prolonging the life of the oil supply [8].

There has to be great concern over the possible effects of severe oil shortages. In 1992 Iraq invaded the adjacent small country of Kuwait and rapidly conquered it, so posing a threat to other oil-producing countries, notably Saudi Arabia. This provoked an immediate response from the western allies, led by the USA. A short

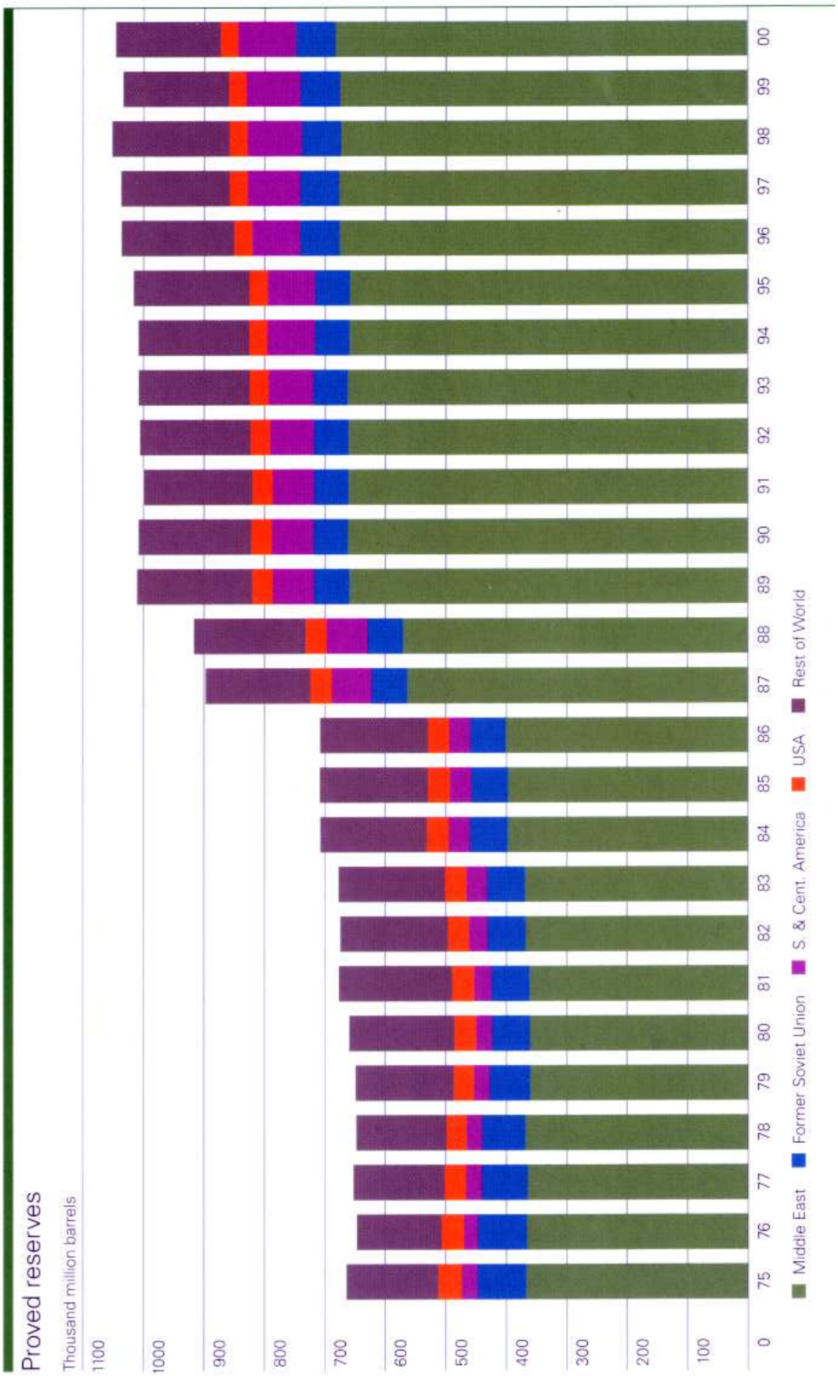
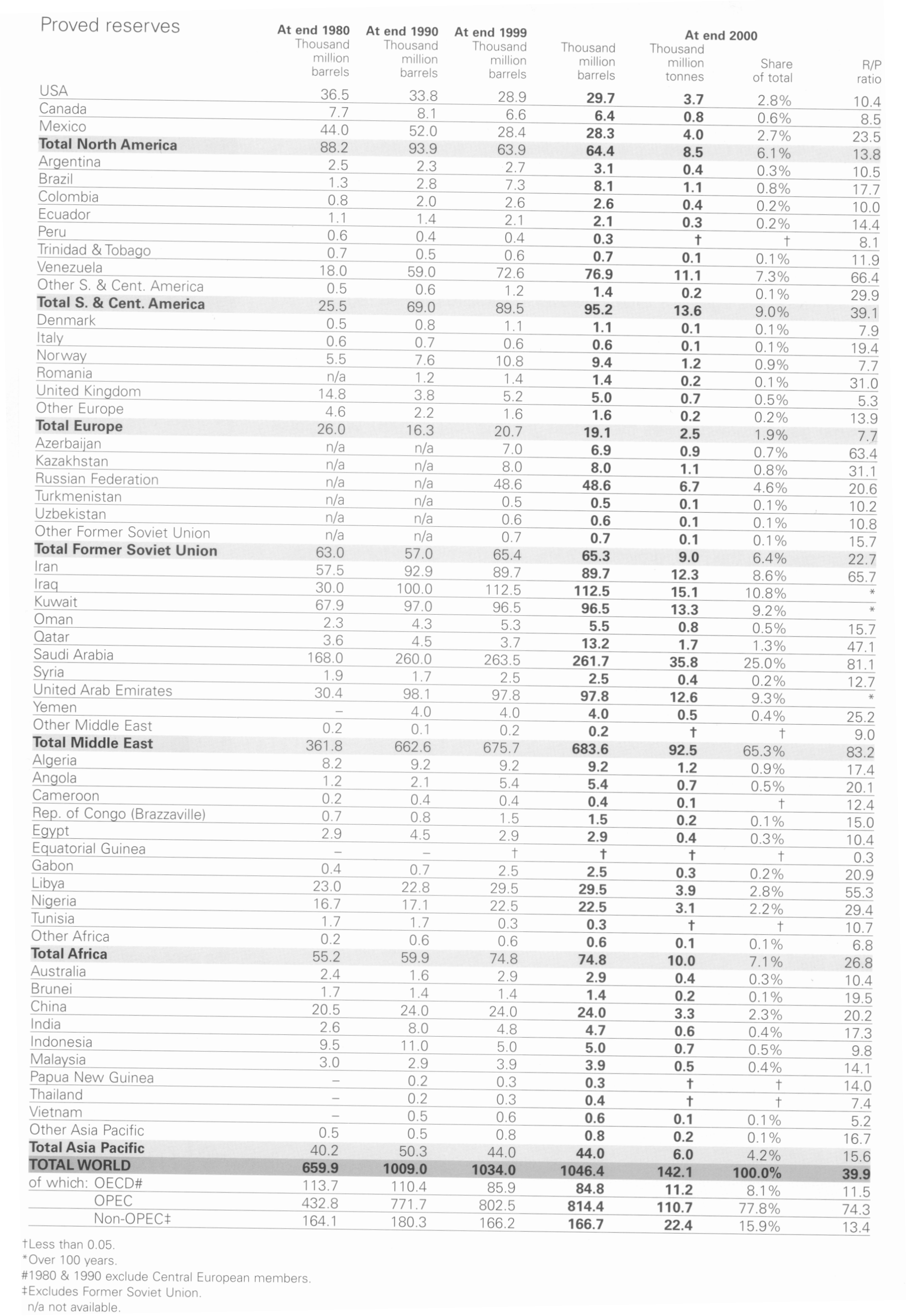


Fig. 5.2. World oil reserves, 1975–2000 [3].

Table 5.2. World reserves (years) of natural crude oil [3].



Proved reserves	At end 1980	At end 1990	At end 1999	At end 2000			
	Thousand million barrels	Thousand million barrels	Thousand million barrels	Thousand million barrels	Thousand million tonnes	Share of total	R/P ratio
USA	36.5	33.8	28.9	29.7	3.7	2.8%	10.4
Canada	7.7	8.1	6.6	6.4	0.8	0.6%	8.5
Mexico	44.0	52.0	28.4	28.3	4.0	2.7%	23.5
Total North America	88.2	93.9	63.9	64.4	8.5	6.1%	13.8
Argentina	2.5	2.3	2.7	3.1	0.4	0.3%	10.5
Brazil	1.3	2.8	7.3	8.1	1.1	0.8%	17.7
Colombia	0.8	2.0	2.6	2.6	0.4	0.2%	10.0
Ecuador	1.1	1.4	2.1	2.1	0.3	0.2%	14.4
Peru	0.6	0.4	0.4	0.3	†	†	8.1
Trinidad & Tobago	0.7	0.5	0.6	0.7	0.1	0.1%	11.9
Venezuela	18.0	59.0	72.6	76.9	11.1	7.3%	66.4
Other S. & Cent. America	0.5	0.6	1.2	1.4	0.2	0.1%	29.9
Total S. & Cent. America	25.5	69.0	89.5	95.2	13.6	9.0%	39.1
Denmark	0.5	0.8	1.1	1.1	0.1	0.1%	7.9
Italy	0.6	0.7	0.6	0.6	0.1	0.1%	19.4
Norway	5.5	7.6	10.8	9.4	1.2	0.9%	7.7
Romania	n/a	1.2	1.4	1.4	0.2	0.1%	31.0
United Kingdom	14.8	3.8	5.2	5.0	0.7	0.5%	5.3
Other Europe	4.6	2.2	1.6	1.6	0.2	0.2%	13.9
Total Europe	26.0	16.3	20.7	19.1	2.5	1.9%	7.7
Azerbaijan	n/a	n/a	7.0	6.9	0.9	0.7%	63.4
Kazakhstan	n/a	n/a	8.0	8.0	1.1	0.8%	31.1
Russian Federation	n/a	n/a	48.6	48.6	6.7	4.6%	20.6
Turkmenistan	n/a	n/a	0.5	0.5	0.1	0.1%	10.2
Uzbekistan	n/a	n/a	0.6	0.6	0.1	0.1%	10.8
Other Former Soviet Union	n/a	n/a	0.7	0.7	0.1	0.1%	15.7
Total Former Soviet Union	63.0	57.0	65.4	65.3	9.0	6.4%	22.7
Iran	57.5	92.9	89.7	89.7	12.3	8.6%	65.7
Iraq	30.0	100.0	112.5	112.5	15.1	10.8%	*
Kuwait	67.9	97.0	96.5	96.5	13.3	9.2%	*
Oman	2.3	4.3	5.3	5.5	0.8	0.5%	15.7
Qatar	3.6	4.5	3.7	13.2	1.7	1.3%	47.1
Saudi Arabia	168.0	260.0	263.5	261.7	35.8	25.0%	81.1
Syria	1.9	1.7	2.5	2.5	0.4	0.2%	12.7
United Arab Emirates	30.4	98.1	97.8	97.8	12.6	9.3%	*
Yemen	–	4.0	4.0	4.0	0.5	0.4%	25.2
Other Middle East	0.2	0.1	0.2	0.2	†	†	9.0
Total Middle East	361.8	662.6	675.7	683.6	92.5	65.3%	83.2
Algeria	8.2	9.2	9.2	9.2	1.2	0.9%	17.4
Angola	1.2	2.1	5.4	5.4	0.7	0.5%	20.1
Cameroon	0.2	0.4	0.4	0.4	0.1	†	12.4
Rep. of Congo (Brazzaville)	0.7	0.8	1.5	1.5	0.2	0.1%	15.0
Egypt	2.9	4.5	2.9	2.9	0.4	0.3%	10.4
Equatorial Guinea	–	–	†	†	†	†	0.3
Gabon	0.4	0.7	2.5	2.5	0.3	0.2%	20.9
Libya	23.0	22.8	29.5	29.5	3.9	2.8%	55.3
Nigeria	16.7	17.1	22.5	22.5	3.1	2.2%	29.4
Tunisia	1.7	1.7	0.3	0.3	†	†	10.7
Other Africa	0.2	0.6	0.6	0.6	0.1	0.1%	6.8
Total Africa	55.2	59.9	74.8	74.8	10.0	7.1%	26.8
Australia	2.4	1.6	2.9	2.9	0.4	0.3%	10.4
Brunei	1.7	1.4	1.4	1.4	0.2	0.1%	19.5
China	20.5	24.0	24.0	24.0	3.3	2.3%	20.2
India	2.6	8.0	4.8	4.7	0.6	0.4%	17.3
Indonesia	9.5	11.0	5.0	5.0	0.7	0.5%	9.8
Malaysia	3.0	2.9	3.9	3.9	0.5	0.4%	14.1
Papua New Guinea	–	0.2	0.3	0.3	†	†	14.0
Thailand	–	0.2	0.3	0.4	†	†	7.4
Vietnam	–	0.5	0.6	0.6	0.1	0.1%	5.2
Other Asia Pacific	0.5	0.5	0.8	0.8	0.2	0.1%	16.7
Total Asia Pacific	40.2	50.3	44.0	44.0	6.0	4.2%	15.6
TOTAL WORLD	**659.9**	**1009.0**	**1034.0**	**1046.4**	**142.1**	**100.0%**	**39.9**
of which: OECD#	113.7	110.4	85.9	84.8	11.2	8.1%	11.5
OPEC	432.8	771.7	802.5	814.4	110.7	77.8%	74.3
Non-OPEC‡	164.1	180.3	166.2	166.7	22.4	15.9%	13.4

†Less than 0.05.
*Over 100 years.
#1980 & 1990 exclude Central European members.
‡Excludes Former Soviet Union.
n/a not available.

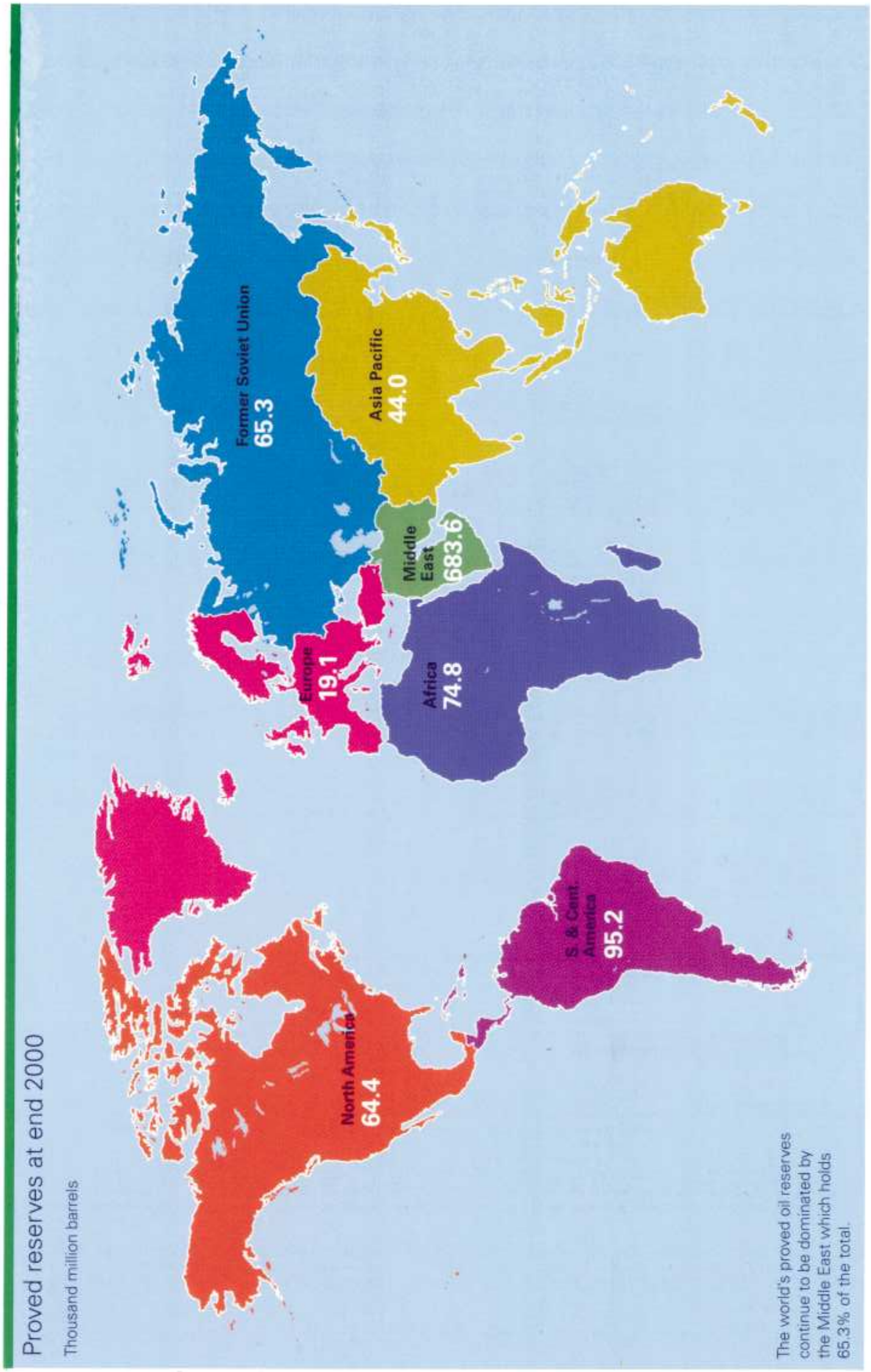
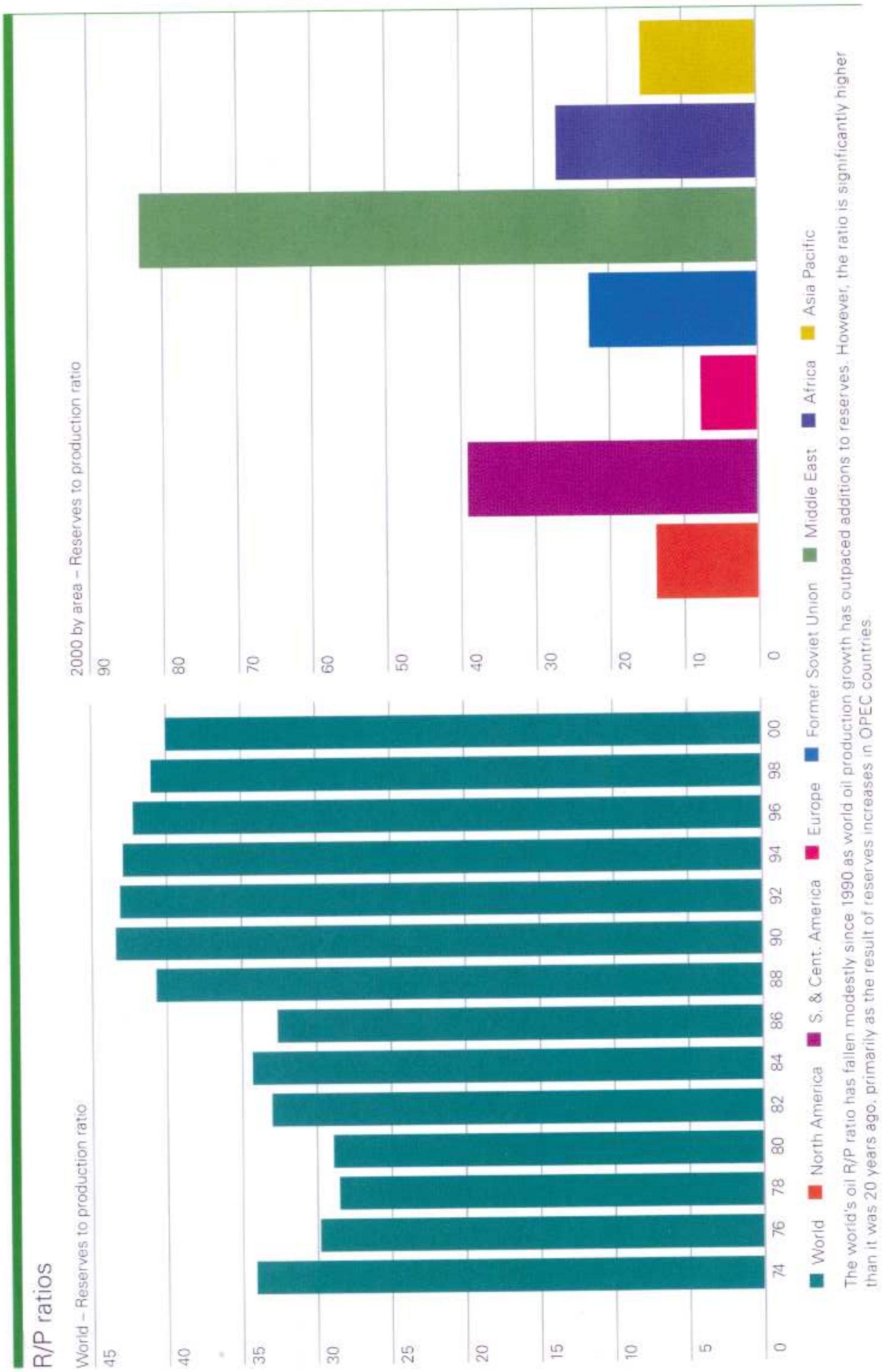

Proved reserves at end 2000
Thousand million barrels
North America
64.4
S. & Cent. America
95.2
Europe
19.1
Former Soviet Union
65.3
Middle East
683.6
Africa
74.8
Asia Pacific
44.0
The world's proved oil reserves continue to be dominated by the Middle East which holds 65.3% of the total.

Fig. 5.3. World oil reserves by area, 2000 [3].



The world's oil R/P ratio has fallen modestly since 1990 as world oil production growth has outpaced additions to reserves. However, the ratio is significantly higher than it was 20 years ago, primarily as the result of reserves increases in OPEC countries.

Fig. 5.4. Oil reserve/production (R/P) ratios by year and geographical area [3].

and brilliantly successful military campaign resulted in an Iraqi withdrawal from Kuwait. But the Middle East remains a region of the world subject to political uncertainties. There can be no guarantee that Middle Eastern oil will continue to be always available to the rest of the world in sufficient quantity and at an acceptable price. This will become of critical importance to the western OECD countries in less than 20 years' time. It is likely that the large reserves in Russia, Azerbaijan and Kazakhstan will become significant.

There is currently (2002) a resurgence of interest in deep water oil exploration. The shallower fields of the continental shelf of the Gulf of Mexico, off the coast of Texas and Louisiana, have been the site of 3000 drilling platforms in the past 50 years. These fields are now largely depleting beyond their economic recovery levels. Several major oil companies are now drilling in the deeper waters of the Mexican Gulf, off-shore West Africa and the continental shelf, west of Scotland. Huge drilling platforms are being designed for flotation rather than for resting on the sea bed. Deep water drilling can cost up to five times as much as shallow water exploration but the world need for oil is enormous. New technologies such as the "tension leg platform" are being used to drill to ocean depths of 4000 ft in areas 150 miles offshore. Exploration is now being developed in the Gulf of Mexico for ocean depths of 8000 ft at 200 miles offshore. It is not known how far and to what depths this technology can proceed.

Several countries along the coast of West Africa are anticipated sites of major deep sea exploration. These include Nigeria, Equatorial Guinea, Gabon, the Republic of the Congo and, most notably, Angola. In terms of reserves the 17 deep water field discoveries to date (2002) have an average field size of 535 million barrels of oil equivalent. The new West African fields have a potential in excess of the deep sea fields in North America [9].

5.4. World Production and Consumption of Crude Oil

5.4.1. *World oil production*

Oil is the world's most important primary fuel, accounting for 40% of the total fuel consumption in 2000 [3]. Data for world oil production in the 11 years to 2000 is given in Table 5.3. In 2000 it is seen that 1112.4/3589.6 or 31% of the world oil production was in the Middle East — by far the biggest component of the total. In Europe oil production is largely offshore, on the NW Europe continental shelf, including the North Sea, shared between Britain and Norway. The former Soviet Union produced more oil than Africa (major producers Algeria, Libya and Nigeria), plus Asia-Pacific (major producers China, Indonesia and Australia). A major new source is being developed (2002) in the Caspian Sea, by the FSU country of Ukraine. Certain countries that are heavy users of oil, notably Japan, have no indigenous oil at all and are not listed in the producer data of Table 5.3. A wider perspective on oil production is given in the chart of Fig. 5.5.

Table 5.3. World oil production [3].

Production*

Million tonnes	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	**2000**	Change 2000 over 1999	2000 share of total
USA	417.1	423.4	413.5	397.5	388.0	384.0	382.5	380.4	368.6	353.0	**353.5**	0.1%	9.8%
Canada	92.3	92.7	96.6	101.7	106.1	111.5	115.1	120.3	124.7	120.6	**126.3**	4.7%	3.5%
Mexico	147.1	154.5	154.5	154.6	155.2	151.3	163.4	170.6	174.4	166.1	**172.1**	3.6%	4.8%
Total North America	656.5	670.6	664.7	653.8	649.2	646.9	661.0	671.3	667.7	639.7	**651.9**	1.9%	18.1%
Argentina	25.9	26.3	29.6	31.6	35.1	38.1	41.6	44.1	44.9	42.7	**41.2**	–3.5%	1.1%
Brazil	32.6	32.2	32.4	33.0	34.3	35.5	40.2	43.1	49.9	56.4	**63.5**	12.6%	1.8%
Colombia	22.7	22.0	22.6	23.4	23.5	30.2	32.4	33.9	39.3	42.5	**36.1**	–15.1%	1.0%
Ecuador	14.9	15.7	16.8	18.0	19.8	20.2	20.1	20.2	19.6	19.5	**20.7**	6.4%	0.6%
Peru	6.6	5.9	5.9	6.4	6.5	6.2	6.1	6.0	6.0	5.8	**5.3**	–8.8%	0.2%
Trinidad & Tobago	7.7	7.5	7.2	6.7	7.0	7.0	6.9	6.6	6.5	6.7	**8.1**	21.1%	0.2%
Venezuela	115.9	129.3	129.6	134.0	142.0	152.4	162.2	171.4	181.0	163.2	**166.8**	2.2%	4.6%
Other S. & Cent. America	3.6	3.6	3.6	4.0	4.3	4.7	4.8	5.6	6.0	6.4	**6.6**	4.1%	0.2%
Total S. & Cent. America	229.8	242.4	247.7	257.0	272.4	294.2	314.3	330.9	353.2	343.1	**348.2**	1.5%	9.7%
Denmark	6.0	7.0	7.8	8.3	9.1	9.2	10.1	11.4	11.4	14.7	**17.8**	21.3%	0.5%
Italy	4.7	4.3	4.5	4.6	4.9	5.2	5.5	6.0	5.6	5.0	**4.6**	–8.6%	0.1%
Norway	81.7	93.3	106.9	114.1	129.4	138.5	155.5	156.9	150.0	149.4	**157.5**	5.5%	4.4%
Romania	8.1	7.0	6.8	6.9	7.0	7.0	6.9	6.8	6.6	6.4	**6.3**	–1.6%	0.2%
United Kingdom	91.6	91.3	94.3	100.2	126.5	129.9	129.7	128.2	130.6	136.6	**126.2**	–7.6%	3.5%
Other Europe	25.3	24.7	24.1	22.4	22.9	21.4	20.0	18.8	18.0	16.7	**16.6**	–0.6%	0.5%
Total Europe	217.5	227.5	244.4	256.6	299.8	311.2	327.6	327.9	322.3	328.7	**329.0**	0.1%	9.2%
Azerbaijan	12.5	11.7	11.1	10.3	9.6	9.2	9.1	9.2	11.4	13.8	**14.9**	8.0%	0.4%
Kazakhstan	25.8	26.6	25.8	23.0	20.3	20.6	23.0	25.8	25.9	30.1	**35.3**	17.1%	1.0%
Russian Federation	515.9	461.9	398.8	354.9	317.6	310.8	302.9	307.4	304.3	304.8	**323.3**	6.1%	9.0%
Turkmenistan	5.7	5.4	5.2	4.4	4.2	4.1	4.4	5.4	6.4	7.1	**7.4**	4.2%	0.2%
Uzbekistan	2.8	2.8	3.3	4.0	5.5	7.6	7.6	7.9	8.2	8.1	**7.5**	–7.4%	0.2%
Other Former Soviet Union	7.9	7.4	7.0	6.6	6.5	6.2	6.4	6.4	6.2	6.0	**6.0**	–0.1%	0.2%
Total Former Soviet Union	570.5	515.8	451.2	403.2	363.7	358.4	353.3	362.0	362.5	369.9	**394.4**	6.6%	11.0%
Iran	161.4	173.4	174.7	182.2	182.6	182.7	183.8	184.1	187.8	175.2	**186.6**	6.5%	5.2%
Iraq	105.1	13.7	25.9	22.6	25.2	27.3	29.9	58.0	105.2	125.6	**128.1**	2.0%	3.6%
Kuwait	46.9	9.2	54.7	97.5	104.1	105.3	105.8	105.7	108.1	99.3	**105.6**	6.4%	2.9%
Oman	34.4	35.5	37.2	38.9	40.6	43.0	44.5	45.1	44.9	45.2	**47.8**	5.8%	1.3%
Qatar	20.6	19.9	23.0	21.3	20.8	21.3	26.4	32.5	35.0	33.7	**37.0**	9.8%	1.0%
Saudi Arabia	341.3	426.7	440.7	431.1	426.1	426.7	434.6	442.1	442.8	410.3	**441.2**	7.5%	12.3%
Syria	21.1	24.5	26.9	29.5	29.4	31.1	30.6	30.1	30.1	30.3	**28.1**	–7.1%	0.8%
United Arab Emirates	104.9	121.1	115.3	111.3	113.1	110.6	114.5	113.6	116.4	105.6	**114.7**	8.6%	3.2%
Yemen	8.7	9.4	8.7	9.9	16.4	16.6	16.8	17.6	18.0	18.8	**20.8**	10.8%	0.6%
Other Middle East	2.4	2.5	2.5	2.5	2.4	2.4	2.3	2.3	2.3	2.3	**2.3**	2.5%	0.1%
Total Middle East	846.8	835.9	909.6	946.8	960.8	967.0	989.2	1031.2	1090.5	1046.2	**1112.4**	6.3%	31.0%
Algeria	57.5	57.7	56.6	56.7	56.4	56.6	59.3	60.3	61.8	63.9	**67.0**	4.8%	1.9%
Angola	23.4	24.5	27.2	24.8	27.4	31.2	35.4	36.5	36.0	36.8	**36.4**	–1.0%	1.0%
Cameroon	7.8	7.2	6.8	6.6	5.8	5.4	5.6	6.3	5.3	4.8	**4.5**	–7.0%	0.1%
Rep. of Congo (Brazzaville)	8.0	8.1	8.6	9.5	9.6	9.3	10.4	11.6	13.6	14.5	**13.7**	–5.9%	0.4%
Egypt	45.5	45.4	46.0	47.5	46.5	46.6	45.1	43.8	43.0	41.4	**39.5**	–4.5%	1.1%
Equatorial Guinea	–	–	0.1	0.2	0.2	0.3	0.9	3.0	4.1	4.5	**5.3**	17.8%	0.1%
Gabon	13.5	14.7	14.5	15.2	16.8	17.8	18.3	18.2	16.9	17.0	**16.4**	–3.8%	0.5%
Libya	68.3	69.0	70.8	67.2	68.6	69.0	69.6	71.1	70.7	68.0	**70.6**	3.8%	2.0%
Nigeria	89.8	93.7	96.9	97.8	97.6	98.1	105.4	113.4	106.5	99.9	**103.9**	4.1%	2.9%
Tunisia	4.6	5.2	5.2	4.7	4.4	4.3	4.2	3.8	3.9	4.0	**3.7**	–6.0%	0.1%
Other Africa	1.8	1.7	1.5	1.8	2.1	2.6	3.3	3.6	3.4	6.7	**12.2**	81.4%	0.3%
Total Africa	320.1	327.2	334.1	332.0	335.4	341.0	357.5	371.6	365.2	361.5	**373.2**	3.2%	10.4%
Australia	28.4	26.9	26.5	24.9	26.9	25.4	26.6	28.8	27.4	24.5	**35.5**	45.1%	1.0%
Brunei	7.4	8.0	9.0	8.6	8.8	8.6	8.1	8.0	7.7	9.0	**9.5**	6.5%	0.3%
China	138.3	141.0	142.0	144.0	146.1	149.0	158.5	160.1	160.2	160.2	**162.3**	1.3%	4.5%
India	34.8	33.1	30.2	29.0	33.2	37.3	36.5	37.3	37.0	36.7	**36.5**	–0.7%	1.0%
Indonesia	71.9	78.3	74.1	74.3	74.3	73.9	74.1	73.1	71.6	66.1	**67.8**	2.5%	1.9%
Malaysia	29.9	31.1	31.7	31.1	31.7	34.0	34.4	35.0	36.6	35.7	**36.2**	1.2%	1.0%
Papua New Guinea	–	–	2.5	5.9	5.7	4.7	5.0	3.6	3.8	4.1	**3.3**	–20.2%	0.1%
Thailand	2.7	3.1	3.4	3.5	3.6	3.5	4.0	4.7	4.9	5.3	**6.8**	28.2%	0.2%
Vietnam	2.7	4.0	5.5	6.3	7.1	7.7	8.9	10.1	12.1	14.6	**16.2**	11.0%	0.4%
Other Asia Pacific	6.7	7.0	7.4	7.3	6.7	6.3	6.8	7.3	6.7	6.4	**6.4**	0.1%	0.2%
Total Asia Pacific	322.9	332.4	332.4	334.8	344.0	350.3	362.9	368.0	367.9	362.7	**380.5**	4.9%	10.6%
TOTAL WORLD	**3164.1**	**3151.9**	**3184.1**	**3184.2**	**3225.2**	**3269.0**	**3365.8**	**3462.9**	**3529.1**	**3451.8**	**3589.6**	**4.0%**	**100.0%**
of which: OECD	892.2	917.4	927.7	927.5	968.2	975.7	1008.2	1021.8	1010.9	986.8	**1010.4**	2.4%	28.1%
OPEC	1183.5	1191.9	1262.4	1295.8	1310.9	1323.8	1365.6	1425.5	1486.9	1410.9	**1489.4**	5.6%	41.5%
Non-OPEC‡	1410.0	1444.2	1470.6	1485.3	1550.7	1586.8	1646.9	1675.4	1679.7	1671.0	**1705.8**	2.1%	47.5%

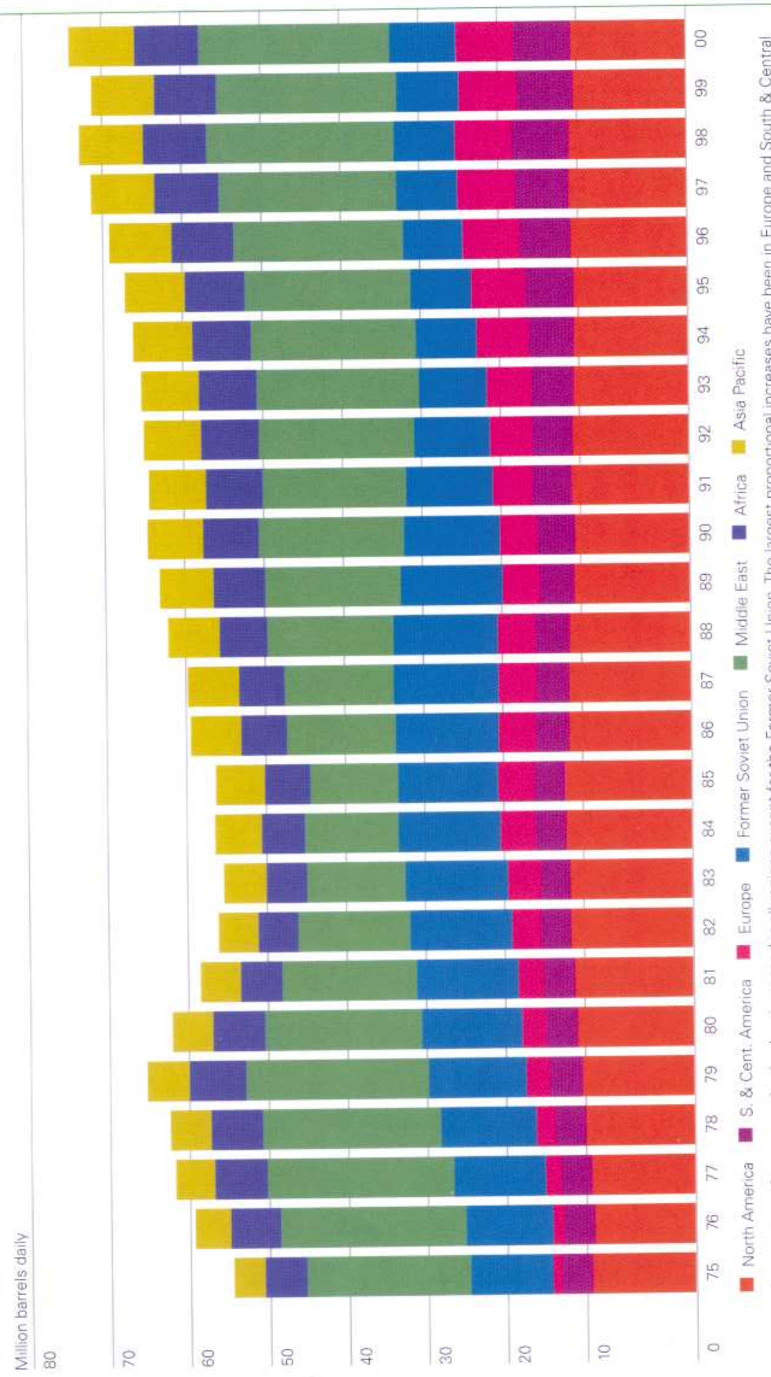
*Includes crude oil, shale oil, oil sands and NGLs (natural gas liquids – the liquid content of natural gas where this is recovered separately). Excludes liquid fuels from other sources such as coal derivatives.

‡Excludes Former Soviet Union.

5.4.2. *World oil consumption*

World oil consumption since 1990 is given in Table 5.4 with the 25-year trends illustrated in Fig. 5.6. Oil consumption continues to increase in all areas of the world except the former Soviet Union. In the 11-year period 1990–2000 world oil consumption increased from 3135.5 mto to 3503.6 mto, a rise of 10.5% from the 1990 figure.

The oil trade patterns in 2000 are illustrated in Fig. 5.7. Oil moves from the Middle East to Japan, SE Asia, Western Europe and northern America (mainly the



Over the last 10 years, production has increased in all regions except for the Former Soviet Union. The largest proportional increases have been in Europe and South & Central America, followed by the Middle East.

Fig. 5.5. World oil production by year and area [3].

Table 5.4. World oil consumption, 1990–2000 [3].

Consumption*

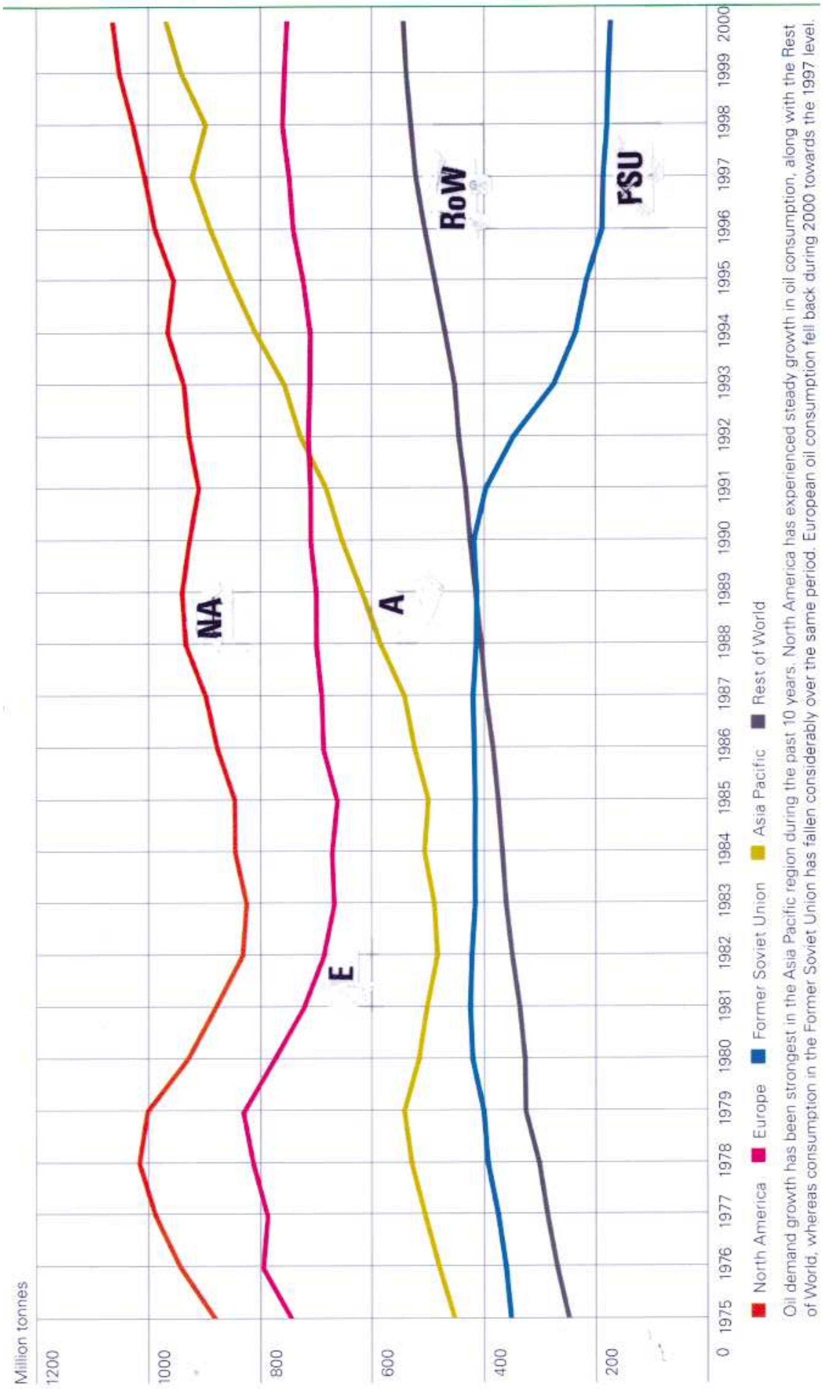
Million tonnes	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	**2000**	Change 2000 over 1999	2000 share of total
USA	781.8	765.6	782.2	789.3	809.8	807.7	836.5	848.0	863.8	888.9	**897.4**	1.0%	25.6%
Canada	77.7	74.8	74.9	77.0	78.7	76.3	78.6	82.1	83.5	82.9	**82.9**	–0.1%	2.4%
Mexico	67.7	70.4	71.2	71.0	77.8	71.4	73.8	77.3	81.2	80.8	**84.3**	4.3%	2.4%
Total North America	927.2	910.8	928.3	937.3	966.3	955.4	988.9	1007.4	1028.5	1052.6	**1064.6**	1.1%	30.4%
Argentina	18.3	19.4	19.6	19.6	19.4	19.5	20.4	21.2	22.1	20.8	**20.1**	–3.5%	0.6%
Brazil	58.4	59.0	62.1	62.9	65.7	69.2	74.1	79.9	83.2	83.2	**84.4**	1.4%	2.4%
Chile	6.6	6.8	7.4	8.0	8.8	9.7	10.6	11.4	11.4	11.7	**11.8**	0.9%	0.3%
Colombia	9.5	9.6	10.6	10.8	11.1	11.8	12.2	12.3	12.0	10.6	**10.5**	–1.7%	0.3%
Ecuador	4.2	4.7	4.6	4.8	5.2	5.1	5.7	6.5	6.6	6.0	**6.5**	7.3%	0.2%
Peru	5.7	5.3	5.5	5.7	6.2	7.1	7.3	7.2	7.3	7.4	**7.0**	–4.5%	0.2%
Venezuela	18.4	18.6	19.7	19.4	19.6	20.0	19.0	20.4	21.6	21.9	**22.6**	3.3%	0.6%
Other S. & Cent. America	45.2	45.1	46.3	47.8	49.9	51.6	52.3	53.2	54.3	55.1	**55.8**	1.4%	1.6%
Total S. & Cent. America	166.3	168.5	175.8	179.0	185.9	194.0	201.6	212.1	218.5	216.7	**218.7**	0.9%	6.2%
Austria	10.8	11.6	11.3	11.4	11.3	11.3	11.6	11.9	12.3	12.1	**11.5**	–4.3%	0.3%
Belgium & Luxembourg	24.8	26.5	27.1	26.5	27.0	26.4	29.4	30.3	31.6	32.4	**33.1**	2.2%	0.9%
Bulgaria	8.8	5.9	6.0	6.2	5.8	5.6	5.5	4.4	4.8	4.9	**5.0**	2.2%	0.1%
Czech Republic	8.4	7.1	6.8	6.9	7.1	8.0	8.4	8.0	8.3	8.2	**7.9**	–3.2%	0.2%
Denmark	9.0	9.1	9.0	9.5	10.1	10.5	11.4	11.1	10.7	10.6	**10.4**	–2.7%	0.3%
Finland	11.0	10.6	10.3	9.9	10.4	9.9	10.3	10.2	10.5	10.7	**10.5**	–1.3%	0.3%
France	89.4	94.6	94.4	91.1	88.2	89.0	91.0	91.7	95.0	96.4	**95.1**	–1.4%	2.7%
Germany	127.3	133.1	134.3	136.3	135.1	135.1	137.4	136.5	136.6	132.4	**129.5**	–2.2%	3.7%
Greece	15.7	15.8	16.1	16.7	16.9	17.6	18.2	18.4	18.2	18.7	**19.1**	2.2%	0.5%
Hungary	9.3	8.0	8.1	7.7	8.1	7.7	7.1	7.1	7.4	7.1	**6.9**	–3.4%	0.2%
Iceland	0.6	0.6	0.7	0.7	0.7	0.8	0.8	0.9	0.9	0.9	**0.9**	4.3%	†
Republic of Ireland	4.4	4.9	5.1	5.1	5.6	5.7	6.0	6.6	7.4	8.3	**8.3**	–1.0%	0.2%
Italy	93.6	92.4	94.5	92.6	92.5	95.5	94.2	94.6	94.7	94.4	**93.0**	–1.4%	2.7%
Netherlands	35.0	35.8	36.5	36.4	36.4	38.0	37.4	39.5	39.4	40.6	**41.8**	3.0%	1.2%
Norway	9.2	8.7	9.0	9.5	9.6	9.6	10.1	10.3	10.0	10.1	**9.4**	–6.5%	0.3%
Poland	15.8	14.9	13.6	14.0	14.8	14.9	17.2	18.2	19.9	19.9	**20.6**	3.6%	0.6%
Portugal	11.1	11.5	12.8	12.0	12.0	12.9	12.1	13.7	15.1	15.4	**15.3**	–0.4%	0.4%
Romania	18.7	15.6	12.7	12.1	11.2	13.5	13.0	13.7	12.0	9.5	**8.9**	–5.8%	0.3%
Slovakia	5.0	4.4	3.9	3.2	3.3	3.2	3.4	3.4	3.3	3.0	**2.8**	–4.9%	0.1%
Spain	48.7	49.4	52.8	51.3	53.5	56.3	58.7	62.0	66.4	68.4	**70.1**	2.5%	2.0%
Sweden	16.4	15.5	16.4	16.1	17.0	16.1	17.4	16.1	16.2	16.1	**15.2**	–5.4%	0.4%
Switzerland	12.8	13.0	13.1	12.3	12.7	11.8	12.2	12.8	13.0	12.6	**12.2**	–3.1%	0.4%
Turkey	22.1	22.1	23.5	27.0	25.8	28.4	29.8	30.0	29.6	29.5	**31.5**	6.8%	0.9%
United Kingdom	82.9	82.5	83.6	84.0	82.9	81.9	83.9	81.3	80.9	79.4	**77.6**	–2.3%	2.2%
Other Europe	19.5	16.9	13.0	13.4	12.9	13.6	15.2	16.5	16.7	16.3	**16.0**	–1.8%	0.5%
Total Europe	710.3	710.5	714.6	711.9	710.9	723.3	741.7	749.2	760.9	757.9	**752.6**	–0.7%	21.4%
Azerbaijan	8.5	8.2	8.1	8.2	8.1	8.5	7.0	6.0	5.9	6.3	**7.4**	17.5%	0.2%
Belarus	24.8	24.0	21.2	14.0	12.8	12.3	9.3	9.6	7.9	6.1	**5.4**	–11.5%	0.2%
Kazakhstan	21.5	21.7	20.3	15.7	12.3	12.0	10.2	10.3	8.2	6.0	**6.2**	3.3%	0.2%
Lithuania	7.5	8.2	4.5	3.9	3.6	3.2	3.3	3.3	3.8	3.1	**2.9**	–4.5%	0.1%
Russian Federation	249.7	243.4	224.4	188.6	162.7	146.1	130.1	129.1	123.7	126.2	**123.5**	–2.1%	3.5%
Turkmenistan	4.4	5.0	4.9	3.2	3.7	3.9	3.0	3.0	4.3	4.5	**4.8**	6.7%	0.1%
Ukraine	63.0	57.5	42.6	24.8	19.8	18.9	14.2	13.8	14.3	13.3	**10.4**	–21.8%	0.3%
Uzbekistan	12.6	11.0	9.1	8.1	7.2	6.7	7.4	6.7	7.0	7.1	**6.8**	–4.2%	0.2%
Other Former Soviet Union	26.7	18.4	12.9	9.2	6.1	5.4	4.2	5.0	4.8	4.7	**5.7**	20.4%	0.2%
Total Former Soviet Union	418.7	397.4	348.0	275.7	236.3	217.0	188.7	186.8	179.9	177.3	**173.1**	–2.3%	5.0%
Iran	47.1	49.0	50.0	50.9	53.4	58.4	60.6	59.0	56.6	58.4	**56.9**	–2.6%	1.6%
Kuwait	5.5	3.7	5.2	4.9	6.0	5.9	7.3	8.0	8.2	8.6	**8.0**	–6.0%	0.2%
Qatar	1.1	0.8	0.8	0.8	0.9	1.0	1.1	1.1	1.2	1.1	**1.1**	2.9%	†
Saudi Arabia	51.2	55.4	51.4	52.1	53.5	51.4	53.7	55.3	58.8	60.9	**62.4**	2.4%	1.8%
United Arab Emirates	12.7	16.5	16.9	17.2	18.2	18.0	17.8	16.3	11.9	13.0	**14.3**	9.4%	0.4%
Other Middle East	47.1	44.0	48.1	49.6	51.0	55.4	57.8	61.1	62.9	65.0	**66.3**	1.9%	1.9%
Total Middle East	164.7	169.4	172.4	175.5	183.0	190.1	198.3	200.8	199.6	207.0	**209.0**	0.9%	5.9%
Algeria	9.2	9.1	9.1	9.1	8.7	8.4	8.1	8.0	8.2	8.1	**8.5**	4.9%	0.2%
Egypt	23.8	23.4	22.7	21.6	21.5	23.3	24.6	26.0	27.3	27.8	**26.2**	–5.6%	0.8%
South Africa	16.6	16.7	17.3	18.0	18.8	20.1	20.7	21.0	21.3	21.8	**22.5**	3.3%	0.6%
Other Africa	45.3	46.4	48.5	50.0	52.0	52.6	53.2	54.5	56.3	58.2	**59.5**	2.2%	1.7%
Total Africa	94.9	95.6	97.6	98.7	101.0	104.4	106.6	109.5	113.1	115.9	**116.7**	0.8%	3.3%
Australia	31.6	30.8	30.9	32.7	34.0	35.3	35.9	37.0	37.0	38.0	**38.7**	1.9%	1.1%
Bangladesh	1.9	1.7	1.8	2.1	2.2	2.8	2.9	3.3	3.1	3.2	**3.3**	3.0%	0.1%
China	110.3	117.9	129.0	140.5	149.5	160.7	174.4	185.6	190.3	207.2	**226.9**	9.5%	6.5%
China Hong Kong SAR	6.3	6.3	8.1	8.3	8.9	9.5	9.3	9.2	8.8	9.3	**9.6**	3.2%	0.3%
India	57.9	58.9	62.1	62.7	67.4	73.0	79.4	83.3	86.8	95.2	**97.6**	2.5%	2.8%
Indonesia	29.8	32.2	35.1	37.6	37.0	39.1	42.4	45.9	43.5	46.8	**51.1**	9.1%	1.5%
Japan	247.7	252.1	257.5	251.9	267.4	267.6	268.8	265.0	253.6	257.3	**253.5**	–1.5%	7.2%
Malaysia	13.0	13.9	14.0	15.6	17.4	17.9	19.0	20.2	19.0	20.3	**20.5**	0.8%	0.6%
New Zealand	4.9	4.9	5.2	5.2	5.6	5.8	5.9	6.1	6.1	6.3	**6.3**	0.7%	0.2%
Pakistan	10.7	11.4	12.4	13.5	14.5	15.8	16.6	17.0	17.6	18.2	**19.6**	7.5%	0.6%
Philippines	11.5	11.1	13.7	14.1	14.9	16.8	17.5	18.8	19.1	18.0	**16.8**	–6.8%	0.5%
Singapore	20.3	20.6	21.7	23.0	26.8	27.9	27.5	29.1	29.2	28.3	**29.1**	2.9%	0.8%
South Korea	49.5	59.9	72.3	79.3	87.0	94.8	101.4	110.3	92.9	99.7	**101.8**	2.1%	2.9%
Taiwan	26.8	27.6	28.4	30.2	32.3	34.7	34.8	36.0	37.2	39.9	**39.8**	–0.3%	1.1%
Thailand	19.6	21.4	23.6	26.8	29.8	34.7	37.5	37.8	35.4	35.4	**34.1**	–3.6%	1.0%
Other Asia Pacific	11.6	11.4	12.5	13.5	14.0	14.8	16.4	17.3	18.1	18.6	**20.2**	8.7%	0.6%
Total Asia Pacific	653.4	682.1	728.3	757.0	808.7	851.2	889.7	921.9	897.7	941.7	**968.9**	2.9%	27.8%
TOTAL WORLD	**3135.5**	**3134.3**	**3165.0**	**3135.1**	**3192.1**	**3235.4**	**3315.5**	**3387.7**	**3398.2**	**3469.1**	**3503.6**	**1.0%**	**100.0%**
of which: OECD	1919.2	1926.2	1973.2	1983.4	2038.0	2046.3	2105.5	2137.0	2142.2	2178.1	**2184.8**	0.3%	62.4%
European Union 15	580.1	593.3	604.2	598.9	598.9	606.2	619.0	623.9	635.0	635.9	**630.5**	–0.8%	18.0%
Other EMEs‡	745.4	767.8	808.1	840.9	884.7	936.0	984.2	1026.0	1039.3	1079.8	**1112.7**	3.0%	31.8%

*Inland demand plus international aviation and marine bunkers and refinery fuel and loss.

†Less than 0.05.

‡Excludes Central Europe and Former Soviet Union.

Note: Differences between these world consumption figures and world production statistics on page 6 are accounted for by stock changes, consumption of non-petroleum additives and substitute fuels, and unavoidable disparities in the definition, measurement or conversion of oil supply and demand data.



Oil demand growth has been strongest in the Asia Pacific region during the past 10 years. North America has experienced steady growth in oil consumption, along with the Rest of World, whereas consumption in the Former Soviet Union has fallen considerably over the same period. European oil consumption fell back during 2000 towards the 1997 level.

Fig. 5.6. Oil consumption by geographical area [3].

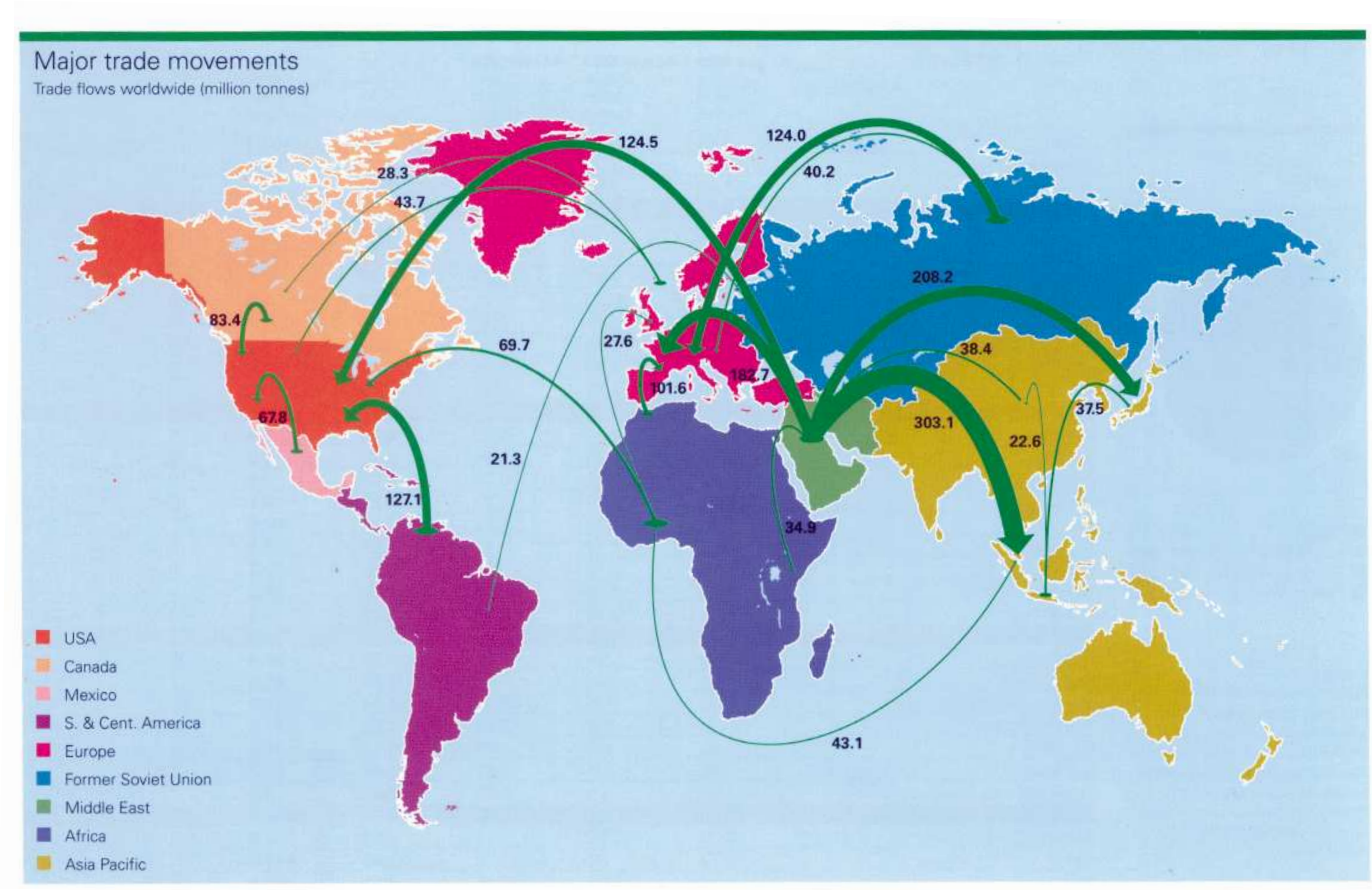
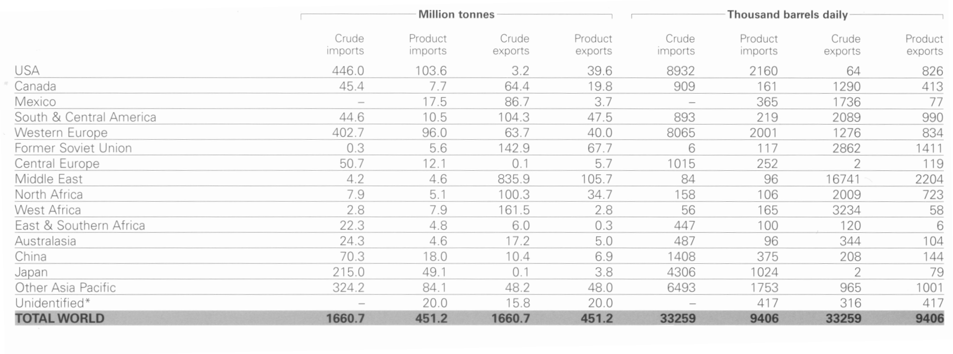

Major trade movements
Trade flows worldwide (million tonnes)
124.5
124.0
40.2
28.3
43.7
208.2
83.4
69.7
27.6
38.4
182.7
101.6
37.5
67.8
303.1
22.6
21.3
127.1
34.9
43.1
USA
Canada
Mexico
S. & Cent. America
Europe
Former Soviet Union
Middle East
Africa
Asia Pacific

Fig. 5.7. World oil trade flows in 2000 [3].

Table 5.5. Oil imports and exports, 2000 [3].



	Million tonnes				Thousand barrels daily			
	Crude imports	Product imports	Crude exports	Product exports	Crude imports	Product imports	Crude exports	Product exports
USA	446.0	103.6	3.2	39.6	8932	2160	64	826
Canada	45.4	7.7	64.4	19.8	909	161	1290	413
Mexico	–	17.5	86.7	3.7	–	365	1736	77
South & Central America	44.6	10.5	104.3	47.5	893	219	2089	990
Western Europe	402.7	96.0	63.7	40.0	8065	2001	1276	834
Former Soviet Union	0.3	5.6	142.9	67.7	6	117	2862	1411
Central Europe	50.7	12.1	0.1	5.7	1015	252	2	119
Middle East	4.2	4.6	835.9	105.7	84	96	16741	2204
North Africa	7.9	5.1	100.3	34.7	158	106	2009	723
West Africa	2.8	7.9	161.5	2.8	56	165	3234	58
East & Southern Africa	22.3	4.8	6.0	0.3	447	100	120	6
Australasia	24.3	4.6	17.2	5.0	487	96	344	104
China	70.3	18.0	10.4	6.9	1408	375	208	144
Japan	215.0	49.1	0.1	3.8	4306	1024	2	79
Other Asia Pacific	324.2	84.1	48.2	48.0	6493	1753	965	1001
Unidentified*	–	20.0	15.8	20.0	–	417	316	417
TOTAL WORLD	**1660.7**	**451.2**	**1660.7**	**451.2**	**33259**	**9406**	**33259**	**9406**

USA). In 2000 the USA had a net inflow (consumption minus production) of 897.4 – 353.5 or 544 mto, which is significantly more than the combined consumption of China and Japan. Import and export figures for various countries and areas for 2000 are given in Table 5.5 [3]. The biggest oil importers were the USA, Western Europe and Japan, while the big exporters were the Middle East, West Africa, the former Soviet Union and Venezuela. More detailed information is obtainable by comparing the production figures of Table 5.3 with the consumption figures of Table 5.4. Oil consumption is growing fastest in China as industrialisation moves forward, which accounts for the steep increasing consumption illustrated in the Asia–Australia (A) characterisation of Fig. 5.6.

5.4.3. *UK oil production and consumption* [10–12]

North Sea oil and gas reserves were first discovered in the 1960s. The North Sea did not emerge immediately as a key non-OPEC oil-producing area, but North Sea production grew as major discoveries continued throughout the 1980s and into the 1990s. Although the region is a relatively high cost producer, its high quality crude oil, political stability, and proximity to major European consumer markets have allowed it to play a major role in world oil and gas markets.

Many of the world's major crude oil prices, Table 5.1, are linked to the price of the North Sea's Brent crude oil. (Brent crude is a blend of North Sea crude oils and does not come exclusively from the Brent field.) Because Brent crude is traded on the International Petroleum Exchange in London, fluctuations in the market are reflected in the price of Brent. Therefore, all other crude oils linked to Brent can be priced according to the latest market conditions.

The North Sea is considered a "mature" area, with few large new discoveries likely to be made. BP (Forties Field) and Shell (Brut) have sold these assets and are "moving out" of the North Sea. In both of the major North Sea producing nations, Norway and the UK, government and industry are taking steps to restructure their oil and gas sectors to make them more internationally competitive.

The UK holds just over 5 billion barrels of proven oil reserves, almost all of which is located in the North Sea. Most of the country's production comes from basins east of Scotland in the northern and central North Sea. The northern North Sea also holds considerable reserves, and smaller deposits are located off-shore in the North Atlantic Ocean, west of the Shetland Islands. There are over 100 oil and gas fields currently onstream, and several hundred companies are active in the area. In 1999, the UK produced the highest volume of oil ever, at 2.95 million barrels per day. Most of the UK's crude oil production ranges in gravity from 30° to 40° API (American Petroleum Institute Gravity). This means that the oil is a "good crude" with ranges in viscosity from "normal oil" to "light oil".

Comparison of the UK oil reserves with oil production is given in Fig. 5.8 [10]. Most high quality crude oil (e.g. North Sea production) is exported, while cheaper, lower quality (mainly from the Middle East) crude oils are imported into the UK for refining, resulting in the trade figures of Table 5.6 [12]. Since the first "surplus" on oil trade (£0.4 billion) in 1980, oil trade has contributed almost £75 billion to the UK balance of payments. The largest surplus (£8.5 billion) in 1985 reflected

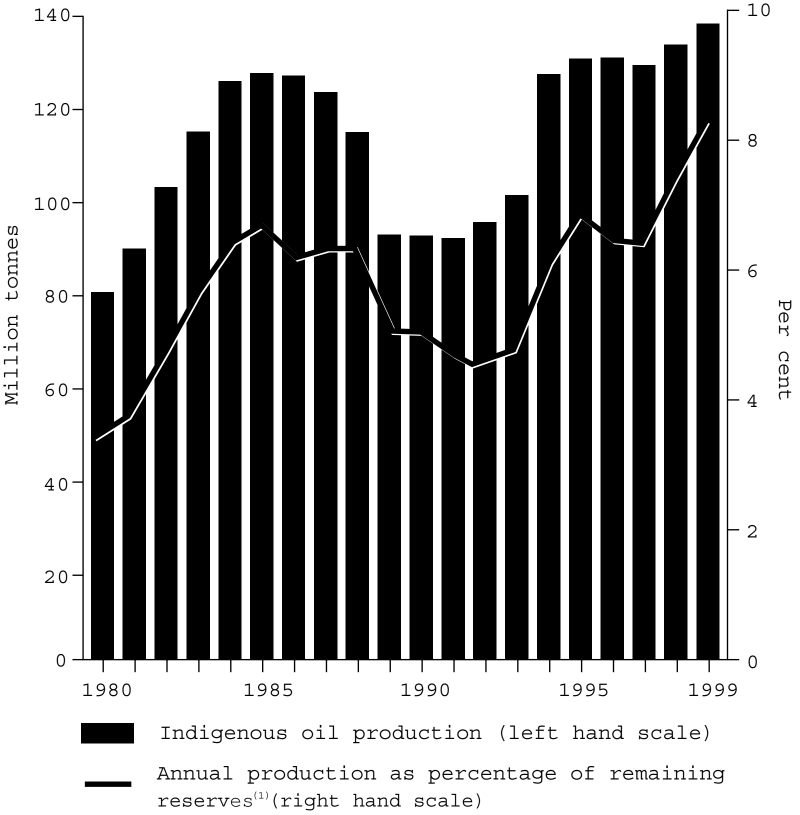


Fig. 5.8. UK oil production and production as a percentage of reserves, 1980–1999 [11].

Table 5.6. Trade in UK crude oil and petroleum products (billions of pounds sterling) [12].

	1970	**1980**	**1990**	**1998**	**1999**	**2000**
Exports	0.3	6.5	8.1	7.0	9.1	15.6
Imports	0.8	6.2	6.4	4.0	4.8	9.0
Net exports	**—0.5**	**0.3**	**1.6**	**3.0**	**4.2**	**6.6**

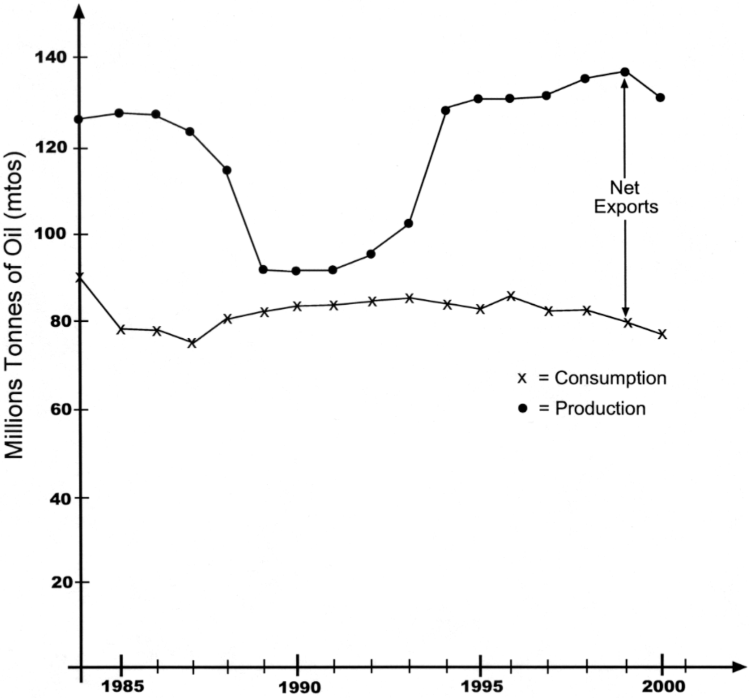


Fig. 5.9. UK oil production and consumption.

high crude oil production and prices. Prices since then have been lower, but with crude oil production (and hence net exports) increasing in recent years, the "surplus" has increased from the lower levels around 1990 and was £4.8 billion (about US$7 billion) in 1999 [12]. The growth of UK oil exports is illustrated in Fig. 5.9, with figures taken from Tables 5.3 and 5.4.

The annual estimate of UK oil reserves remaining in known fields has not varied much over the last 20 years, despite a large increase in the amount of oil extracted annually. This is due to new discoveries being made and new technology allowing the exploitation of discoveries that were previously regarded as not viable.

An area with potential for new production is a remote area of the North Atlantic between the Shetland Islands and the Faroe Islands. A territorial dispute between

Table 5.7. UK petroleum use (Mtonnes) [12].

	1980	**1990**	**1998**	**1999**	**2000**
Energy uses[1]					
Petrol	19.2	24.3	21.9	21.8	21.4
DERV fuel	5.9	10.7	15.1	15.5	15.6
Aviation turbine fuel	4.7	6.6	9.2	9.9	10.7
Burning oil	2.1	2.1	3.6	3.6	3.8
Gas oil	11.6	8.0	7.3	6.7	6.6
Fuel oils	22.7	14.0	5.4	4.5	3.4
Other	4.3	4.9	5.2	5.2	4.9
Total energy uses	**70.5**	**70.6**	**67.7**	**67.2**	**66.4**
Of which:					
Transport fuels	31.9	43.5	47.8	48.5	49.2
Non-energy uses	**7.0**	**9.2**	**10.7**	**10.8**	**10.1**
Total deliveries	**77.5**	**79.8**	**78.4**	**78.0**	**76.5**

[1] "Energy uses" includes uses for transformation (e.g. electricity generation) and energy industry own use (e.g. refinery fuels).

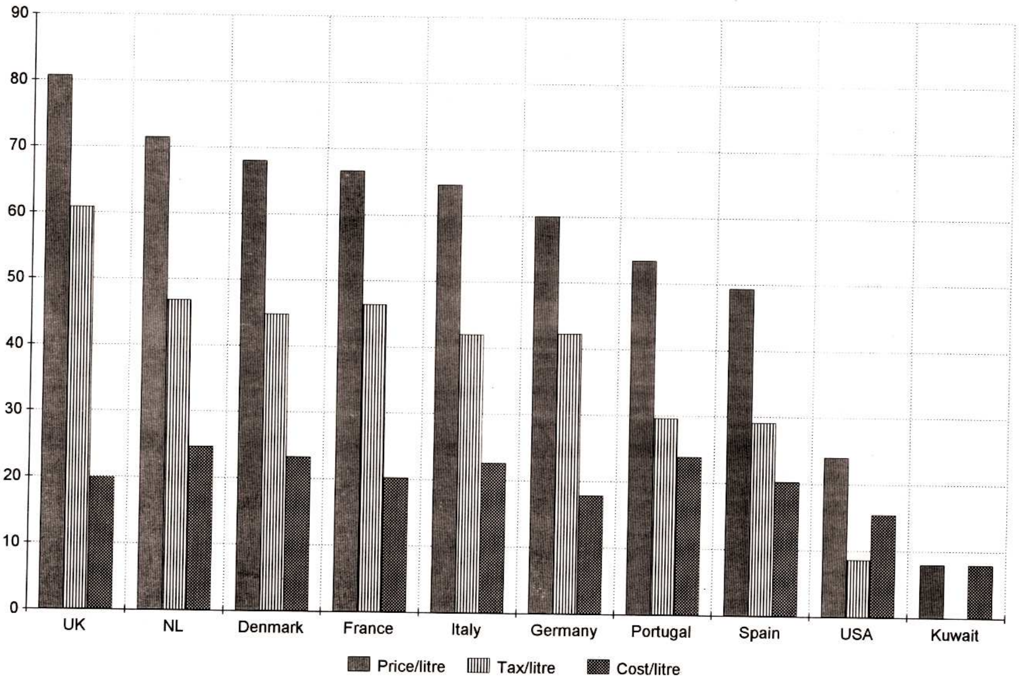


Fig. 5.10. Average unleaded fuel prices (2000).

the government of the Faroe Islands (the Faroe Islands are a self-governed part of Denmark) and the UK prevented exploration until an agreement was reached in the summer of 1999. A licensing round for Faroese development was completed in late May of 2000. A UK licensing round for the Atlantic Ocean, north of Scotland and west of the Shetland Islands, was postponed in May 2000 to allow time to implement the European Commission Habitats Directive, which requires governments to assess potential environmental damage before allowing drilling [10].

The distribution of applications of the use of oil in the UK is shown in Table 5.7. Over the period since 1980 the use of fuel oil has declined, representing a move towards natural gas as the preferred source of energy by electricity generators and by industry. Transport fuel growth has slowed in recent years, with a switch being seen from motor spirit to DERV fuel (i.e. diesel) fuel, but with continued growth in aviation turbine fuel use.

Comparisons of the pump prices of gasoline in various European countries with the costs in the USA and Kuwait are given in Fig. 5.10. Prices are given in terms of cost/litre, since the litre is the metric standard (1 litre = 1/3.785 = 0.264 US gallon). All of the European countries impose a significant taxation levy on their gasoline. It is notable that the pump price of gasoline in the USA is smaller than one-half the European average and carries relatively little taxation. Britain has, by far, the highest pump price and also carries the largest taxation levy. The actual cost of the fuel is roughly the same in all the European countries — it is the level of taxation that creates disparities in the purchase price.

5.4.4. *US oil production and consumption*

The gap between US oil consumption and production is steadily growing, Fig. 5.11. It is seen from Fig. 5.7 that the USA is a massive importer of oil from all of the world's major sources.

Gasoline, one of the main products refined from crude oil, accounts for just about 17% of the energy consumed in the USA. The primary use is in automobiles and light trucks, but also in boats, recreational vehicles, and farm and other equipment. While gasoline is produced year-round, extra volumes are made in time for the summer driving season. Gasoline is delivered from oil refineries mainly through pipelines to a massive distribution chain serving 176,000 retail gasoline stations throughout the USA. There are three main grades of gasoline: regular, mid-grade and premium. Each grade has a different octane (fuel density) level. Price levels vary by grade, but the price differential between grades is generally constant.

The cost of producing and delivering gasoline to consumers includes the cost of crude oil to refiners, refinery processing costs, marketing and distribution costs, taxes and, finally, the retail station costs. The prices paid by consumers at the pump reflect these costs, as well as the profits (and sometimes losses) of refiners,

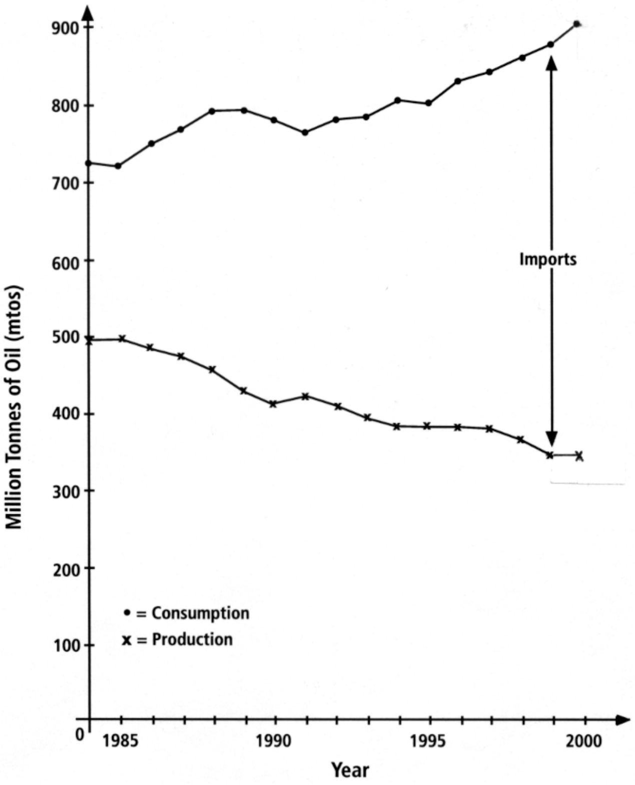


Fig. 5.11. US oil production and consumption.

marketers, distributors and retail station owners.

Federal, state and local taxes are a large component of the retail price of gasoline. Taxes (not including county and local taxes) account for approximately 28% of the 2003 cost of a gallon of gasoline. Within this national average, federal excise taxes are 18.4 cents per gallon and state excise taxes average 19.96 cents per gallon. Also, seven states levy additional state sales taxes, some of which are applied to the federal and state excise taxes. Additional local county and city taxes can have a significant impact on the price of gasoline. Refining costs and profits constitute about 14% of the retail price of gasoline. This component varies from region to region due to the different formulations required in different parts of the country. Distribution, marketing and retail station costs and profits combined make up 12% of the cost of a gallon of gasoline. Approximately one-third of the service station outlets are (2002) company stations, i.e. are owned or leased by a major oil company and operated by its employees. The remainder are operated by independent dealers free to set their own prices. The price at the pump reflects both the retailer's purchase cost for the product and the other costs of operating the service station.

It also reflects local market conditions and factors, such as the desirability of the location and the marketing strategy of the owner. When crude oil prices are stable, retail gasoline prices tend to gradually rise before and during the summer, when people drive more, and fall in the winter. Good weather and vacations cause US summer gasoline demand to average about 6% higher than during the rest of the year. If crude oil prices remain unchanged, gasoline prices typically increase by 5–6 cents per gallon during the summer [13].

The USA is the world's largest consumer of oil, both in absolute terms, Table 5.4, and (except for Singapore) in per capita terms, Figs. 5.12 and 5.13 [14]. America is the dominant world power in economic and military terms, making the President of the USA the most important and influential national leader in the world.

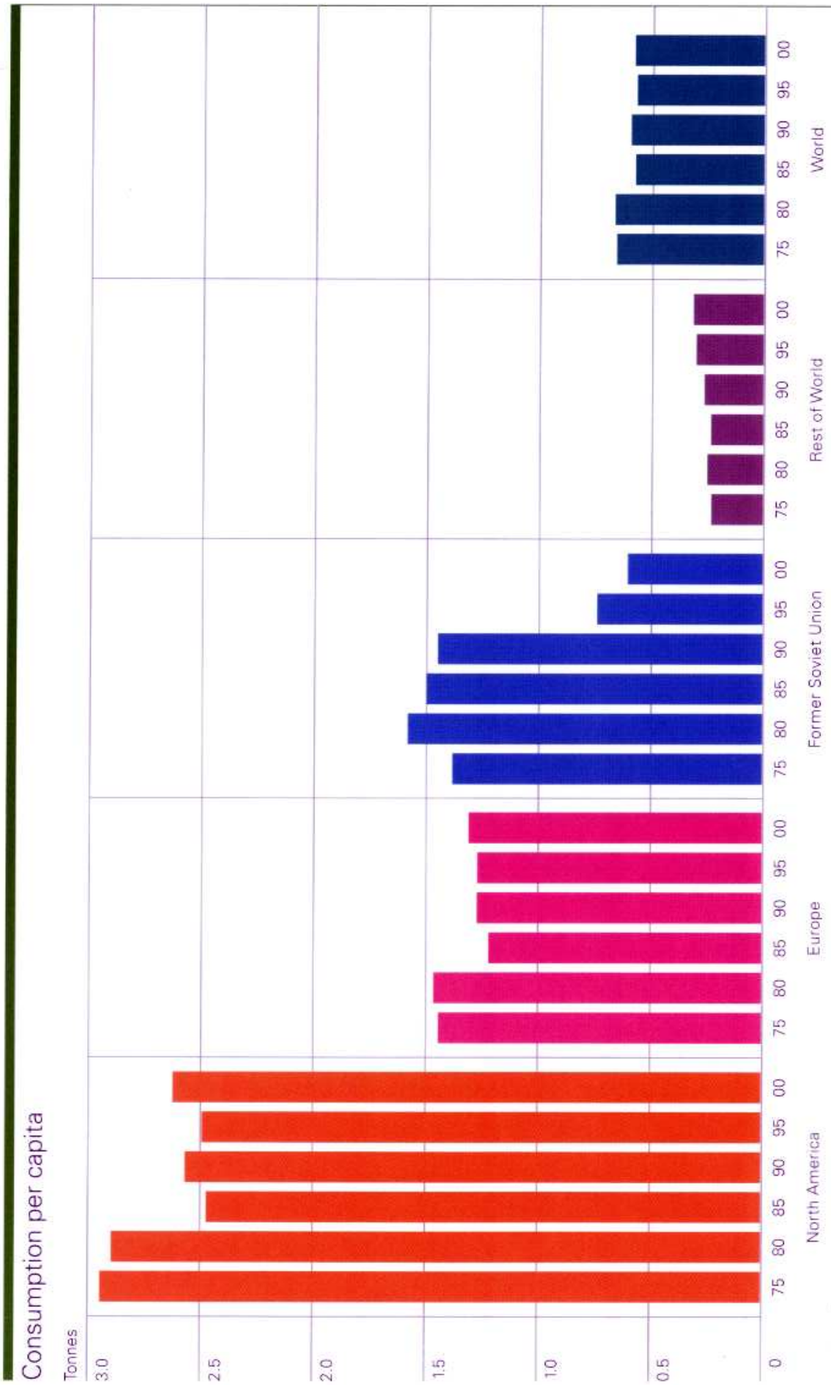
It was noted in Sec. 5.2 that the price of crude oil is usually negotiated between the major oil companies (dominated by US companies) and the OPEC consortium (dominated by Saudi Arabia). In the present aftermath of the 1991 Gulf War, Saudi Arabia enjoys the military protection of the USA. The US-led invasion of Iraq in 2003 has not caused any great changes in oil prices. The OPEC countries outside the Middle East (principally Nigeria and Indonesia) do not appear disposed to act unilaterally to oppose or break the cartel price.

The pump price of gasoline in the USA has always been low. In 2001 the pump price fluctuated between $1.10 and $1.50 per US gallon in response to several economic factors as well as different regional costs and levies, which is roughly one-third the cost in Western Europe.

Gasoline prices in the USA are a matter for the Americans and not for foreign interference. It remains an intriguing situation, however, that the pump price of gasoline in the USA plays so prominent a part in the availability, use and price of the world's most sought-after fuel.

The USA is a vast country, roughly the same size as Europe, and the citizens have always been mobile and had the privilege of driving private cars, often for long distances. Some annual travel information for the USA and some EEC countries, given in Fig. 5.14, clearly shows the extensive car driving habits of Americans. Although this is slightly dated the overall picture is still (2002) true.

The 1973 oil crisis had the ultimate major effect of reducing the sizes of cars driven by most Americans to about the same size as standard European and Japanese cars, although engine size is creeping up again. From the late 1970s there has been a significant reduction in the gasoline used per passenger-mile in the USA [15]. It is difficult to imagine that there will be any further substantial voluntary change in American driving habits. Moreover, the automobile industry in the USA is a major component of the national economy and labour force. Freight has to travel great distances to consumers because of the geography of US infrastructure, and these transport costs affect prices. In addition to energy use, oil forms a major industrial resource for the manufacture of plastics and pharmaceuticals.



Oil consumption per capita varies greatly between regions. Consumption is strongly influenced by levels of economic development and trends in income (GDP) per capita. At the global level, oil consumption per capita was much the same in 2000 as in 1985. Modest increases in North America, Europe and the Rest of World have been offset by a major fall in the Former Soviet Union.

Fig. 5.12. Oil consumption per capita, 1975–2000 [3].

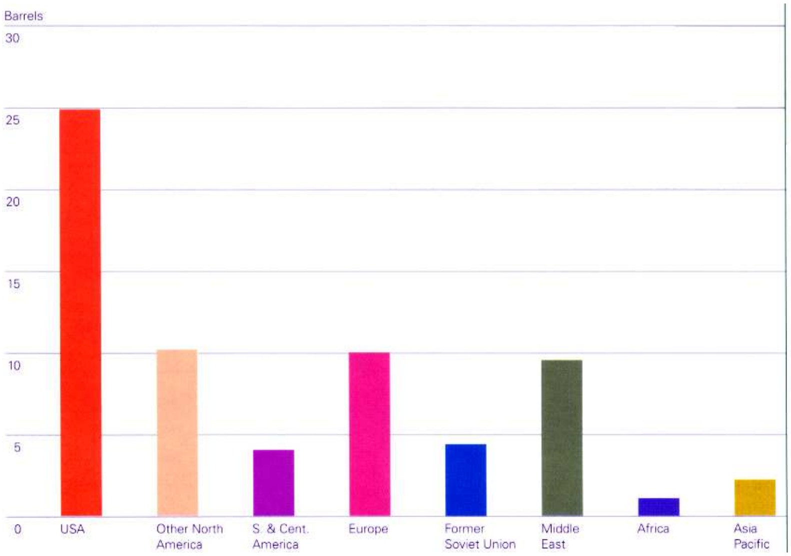


Fig. 5.13. Oil consumption per capita in 2000 [14].

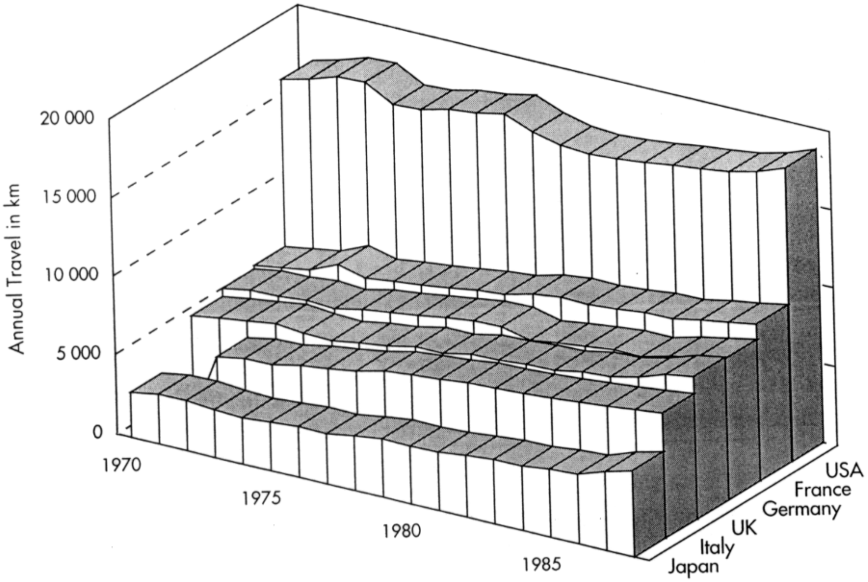


Fig. 5.14. Annual per capita car travel, 1970–1988 [13].

5.5. Synthetic Crude Oil

There are vast underground repositories of potential oil-bearing materials in the form of oil shale and tar sands in North America (discussed below). At present these are not commercially viable. Will the international price of crude oil ever again rise high enough to make this form of oil exploitation competitive with other options [1, 2, 16]?

5.5.1. *Shale oil*

Oil shale is a fairly commonly occurring sedimentary rock containing a solid composite of hydrocarbons called kerogen (approximate composition 80% C, 10% H_2, 6% O_2, 3% N and 1% S). Kerogen is the chemical precursor of oil and gas via a number of complex geochemical processes mainly related to temperature and time. The shale is intractably buried into its containing rock, mud and clay. When oil shale is burned it forms wax. One of the many ancient names for oil shale is "the rock that burns". Known deposits constitute a vast reserve of potential oil-bearing material, but the problem of extraction poses formidable technical, environmental and economic problems. Oil from shale cannot be obtained by drilling bore-holes and collecting crude oil as it bubbles out. The necessary industrial processes are huge in scale and expense.

The USSR and China were operating major oil shale developments in the early 1980s. Up to 100,000 tonnes/year of shale oil was manufactured in Scotland in the 1950s but this was closed down in 1962. The world's largest known deposits of oil shale are in four giant basins in the western USA, covering parts of the states of Wyoming, Colorado and Utah.

Two methods have been considered for obtaining oil from shale:

(i) Mining and processing the rock, and (ii) in situ combustion.

(i) Oil shale mining

Oil shales cannot usually be strip (i.e. open-cast) mined but require sub-surface mining, as in the UK coal industry. Only the richest workings justify the expense. When the extracted oil-bearing shale rock is broken up and heated to temperatures greater than 480°C the kerogen decomposes, producing an oily vapour that condenses to viscous shale oil, containing up to 80% of the original energy in the kerogen. This shale oil often contains nitrogen compounds and sulphur that need to be removed by further processing to obtain an acceptable form of crude oil [17].

Every 100 tonnes of crushed rock leaves about 90 tonnes of waste processing and, moreover, the volume of the waste is 40% greater than its original solid rock. A high energy input is required to decompose the oil shale/rock into products. Obtaining the same amount of energy from an oil shale, which typically yields a barrel of oil per tonne of rock, requires five times as much mining as coal [2]. Large quantities of saline-rich waste rock would need to be disposed of in above-ground sites, like deep coal-mining waste. This would raise the possibility of ground contamination as the rock is washed by rainwater.

A further disadvantage of mining oil shale is that pulverising the rock creates large clouds of fine dust rising high into the air. In the USA there would be a danger of wind-borne dust contaminating neighbouring wheat-growing states like Kansas and Nebraska. In addition, processing of the rock requires three barrels of water for each barrel of oil produced and might require drastic modification of the local water supplies. The main "oil shale deposits" occur in desert/arid areas.

(ii) In situ combustion

Some of the environmental objections to the mining method described in the preceding section can be overcome by in situ retorting, in which the quarrying and processing is carried out underground. A cavity is hollowed out by sinking boreholes and using hydraulic power or explosives to break up the shale. Heat is then applied from above, Fig. 5.15, by injecting hot liquids or gases to combust the shale. As the fire burns down through the rubble the decomposed kerogen products flow out at the bottom and are pumped out of the mine [17, 18]. This involved industrial process is very expensive and difficult to accomplish.

The high cost of in situ extraction together with the extensive environmental protection required make oil shale mining prohibitively expensive at the present time. There are massive potential sources of shale oil, but at the current (2002) cheap price of Middle East crude oil of about US$20/barrel it will not be mined. It is necessary for the international price of crude oil to return to at least the

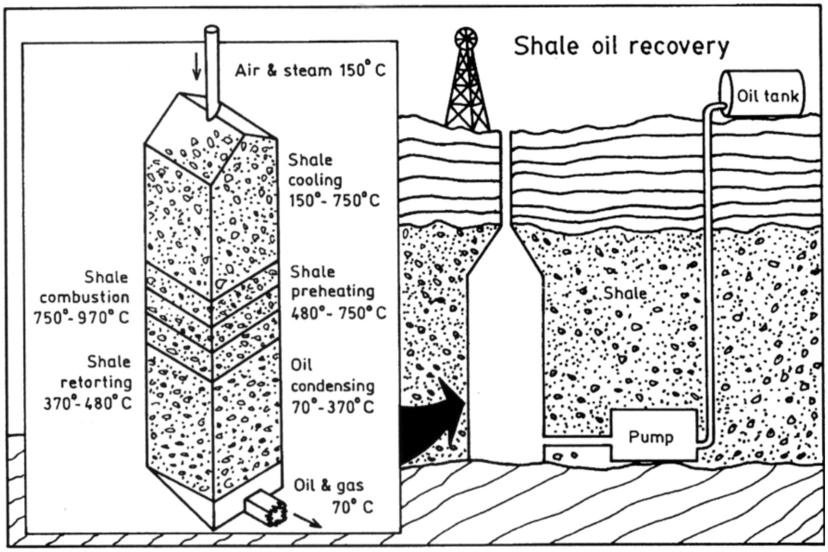

Shale oil recovery
Air & steam 150° C
Shale cooling 150°- 750°C
Shale preheating 480°- 750°C
Oil condensing 70°-370°C
Oil & gas 70° C
Shale combustion 750°-970° C
Shale retorting 370°-480° C
Oil tank
Shale
Pump

Fig. 5.15. Shale oil recovery [18].

early 1980s figure of US$35/barrel or more for shale oil exploration to become commercially viable. In the oil business there is a well-held theory that the major oil producers will always keep the price of crude oil lower than that required to develop oil shale/tar sand deposits.

Although the use of tar sands as a source of oil is not yet active, there is renewed interest in the possible use of shale gas [19]. This is explored more fully in the following chapter.

5.5.2. *Tar sands*

Tar sands are beds of sand impregnated with the naturally occurring viscous petroleum material bitumen, sometimes called "sticky oil" or "heavy oil". The name "tar" is a misnomer — the sand beds do not contain tar, which is a manufactured product. Originally the sands were "oil reservoirs", usually containing conventional oil, which had come near to the surface. This conventional oil, containing a complex mixture of hydrocarbons (including long-chain molecules), was changed by reaction with water containing micro-organisms and oxygen from the surface. In this weathering process the long-chain hydrocarbons are removed to produce tar sands or heavy oil.

The two largest known deposits are the Athabasca Tar Sands in Alberta, Canada, and the Orinoco Heavy Oil Belt in Venezuela. These deposits lie underground but some of the material is sufficiently near the surface (i.e. within 300 ft) to be accessible by open-casting mining. For the deeper deposits it would be necessary to use in situ methods of the type described in the preceding section.

Estimates of the world resources of oil from tar sands vary between 300–800 billion tonnes, although 90% of this would require sub-surface mining or in situ methods. Near surface deposits might yield up to 30 billion tonnes [20]. This is about $8\frac{1}{2}$ times the 2000 world oil consumption, in addition to the known reserves of crude oil.

The most successful commercial production, at Athabasca, had approached 200,000 barrels per day, equivalent to 40 million tonnes/annum, by the early 1980s. The plant used hot water to separate out the bitumen from the sand. This was then refined and upgraded by a fluidised-bed coking process and treated with hydrogen to remove impurities, resulting in high-grade synthetic crude oil. About two tonnes of sand are needed to produce a barrel of oil. An annual output of 40 million tonnes of oil would create almost 600 million tonnes of waste material, posing a formidable environmental waste-disposal problem. Associated environmental effects include possible contamination of groundwater, air pollution and the destruction of natural drainage patterns.

In the early 1980s estimated costs of producing synthetic crude oil from tar sands or oil shales were in the range US$40–$80 per barrel, which was barely economical even then but acceptable as prototype figures that could be expected to reduce with experience. This did, however, match the then current and anticipated prices of oil. The fall in price of Middle East crude oil to about US$20/barrel in 1984, Fig. 5.1, made the tar sands and oil shale projects completely unviable and they have largely been "mothballed" until quite recently [21]. At the present period (2002), an international price of US$35/barrel minimum would be needed to revive the commercial interest, whereas the latest price figure is around US$20/barrel. Nonetheless, the repository of tar sands in Western Canada represents a great opportunity for future development. Interest has been revived by better technology and greater investment [22].

5.6. Environmental Issues

The environmental hazards of land-based oil exploration, refining and transportation include damage to wildlife preserves, interference with animal migration routes,

Fig. 5.16. Offshore oil rig [23].

atmospheric emissions and the rehabilitation of land after mining or pipe-laying operations.

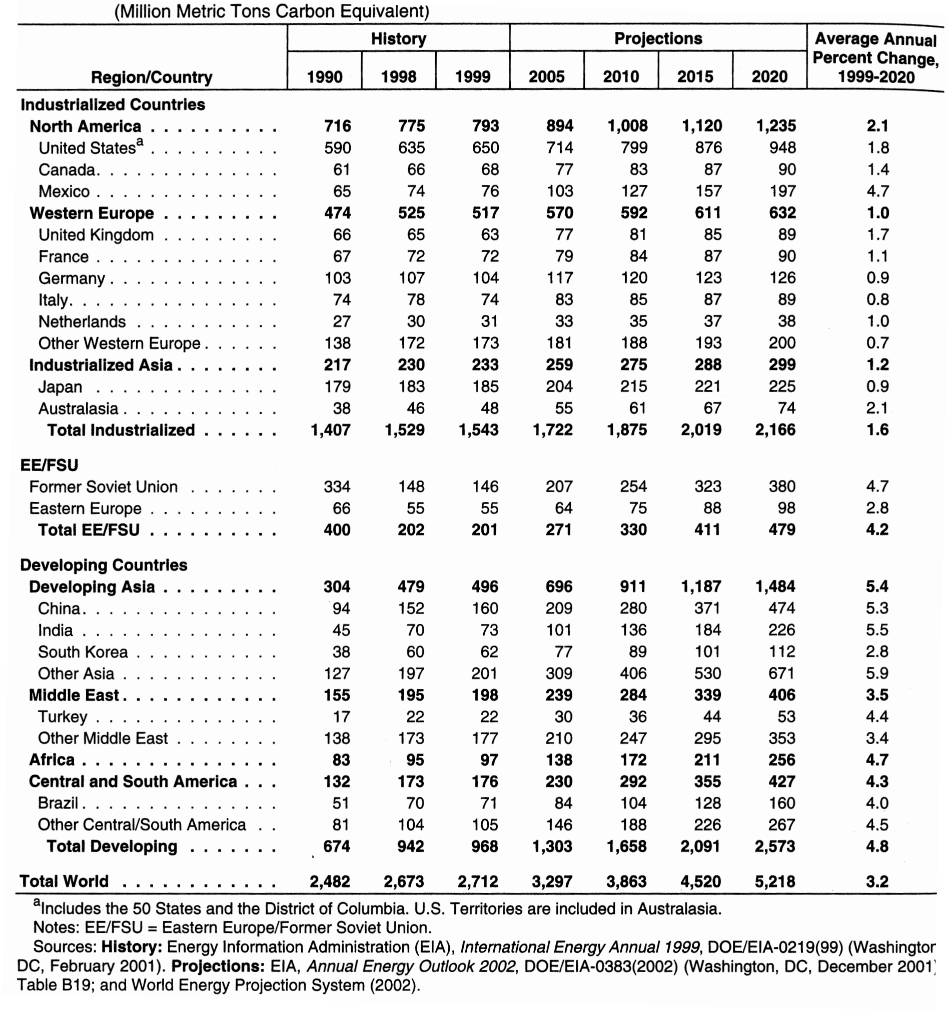
Corresponding hazards exist with regard to offshore oil platforms. A typical platform, Fig. 5.16, is an oil production factory that rests on the sea bottom on giant hydraulic legs [23]. The staff lives on board for weeks at a time and essential supplies of food and mail are brought out by helicopter or boat. Sometimes crude oil from the rig sites is pumped ashore directly through pipes on the sea-bed. At some sites the crude oil is pumped into oil tanker ships for distribution to refineries all over the world. About one quarter of world oil production is from offshore fields. An offshore oilfield represents environmental risks such as contamination of the sea-bed, damage to shoals of fish, interference with fish migration routes and the pollution of nearby beaches and coastlines due to leaks and spillages. A large number of rigs in a small area such as in the North Sea or along the Gulf of Mexico and the California coastlines can create artificial reef effects.

An offshore oil platform, like any other component of the petroleum industry, represents an explosion risk. On the whole the safety record of the industry is very good. The worst single accident in the oil industry occurred in the North Sea field in 1988, when a catastrophic explosion and fire at the Piper-Alpha rig, operated by Occidental Petroleum, destroyed the rig and killed 167 workers, as mentioned in Sec. 2.6.3 of Chapter 2.

The biggest profile environmental risks of the oil industry are large-scale spillages from oil tankers. In 1994 the world total of registered oil tankers numbered 3192 vessels. The Exxon/Mobil conglomerate operated more than 500 tankers and supertankers in 1999. In Great Britain and Ireland tanker wrecks such as the "Torrey Canyon" and "Amoco Cadiz" caused oil contamination of shorelines and widespread destruction of coastal and marine wildlife. The world's biggest oil tanker disaster was the wrecking of the "Exxon Valdez" in Prince William Sound, Alaska, in 1987. The ship ran onto rocks that punctured the double hull tanks laden with crude oil. Massive spillage occurred, necessitating a very expensive clean-up operation along the coastline. Sophisticated techniques have now been developed for containing, recovering and dispersing oil spills. The effects of oil contamination on the marine environment are not always irreversible. Possibly the worst feature of large-scale oil spillages is that the long-term effects are not known. Globules of oil come to rest not only on the sea-bed and coastline but are swept away by ocean currents to be deposited all over the world.

Both land-based and offshore oil production contribute to environmental pollution in the form of gaseous carbon emissions. Historical and projected future carbon dioxide emissions due to oil are shown in Table 5.8 [8]. Comparison with the total world carbon dioxide emission figures in Table 2.8 of Chapter 2 shows that oil-based emissions account for rather less than one-half of the total. In other words, carbon dioxide emissions due to the oil industry and to oil use are roughly equivalent to those from coal (Table 4.9 of Chapter 4) and natural gas (Table 6.5 of Chapter 6)

Table 5.8. World carbon dioxide emissions from oil use by region, high economic growth case, 1990–2020.



(Million Metric Tons Carbon Equivalent)

Region/Country	History			Projections				Average Annual Percent Change, 1999-2020
	1990	1998	1999	2005	2010	2015	2020	
Industrialized Countries								
North America	**716**	**775**	**793**	**894**	**1,008**	**1,120**	**1,235**	**2.1**
United States[a]	590	635	650	714	799	876	948	1.8
Canada	61	66	68	77	83	87	90	1.4
Mexico	65	74	76	103	127	157	197	4.7
Western Europe	**474**	**525**	**517**	**570**	**592**	**611**	**632**	**1.0**
United Kingdom	66	65	63	77	81	85	89	1.7
France	67	72	72	79	84	87	90	1.1
Germany	103	107	104	117	120	123	126	0.9
Italy	74	78	74	83	85	87	89	0.8
Netherlands	27	30	31	33	35	37	38	1.0
Other Western Europe	138	172	173	181	188	193	200	0.7
Industrialized Asia	**217**	**230**	**233**	**259**	**275**	**288**	**299**	**1.2**
Japan	179	183	185	204	215	221	225	0.9
Australasia	38	46	48	55	61	67	74	2.1
Total Industrialized	**1,407**	**1,529**	**1,543**	**1,722**	**1,875**	**2,019**	**2,166**	**1.6**
EE/FSU								
Former Soviet Union	334	148	146	207	254	323	380	4.7
Eastern Europe	66	55	55	64	75	88	98	2.8
Total EE/FSU	**400**	**202**	**201**	**271**	**330**	**411**	**479**	**4.2**
Developing Countries								
Developing Asia	**304**	**479**	**496**	**696**	**911**	**1,187**	**1,484**	**5.4**
China	94	152	160	209	280	371	474	5.3
India	45	70	73	101	136	184	226	5.5
South Korea	38	60	62	77	89	101	112	2.8
Other Asia	127	197	201	309	406	530	671	5.9
Middle East	**155**	**195**	**198**	**239**	**284**	**339**	**406**	**3.5**
Turkey	17	22	22	30	36	44	53	4.4
Other Middle East	138	173	177	210	247	295	353	3.4
Africa	**83**	**95**	**97**	**138**	**172**	**211**	**256**	**4.7**
Central and South America	**132**	**173**	**176**	**230**	**292**	**355**	**427**	**4.3**
Brazil	51	70	71	84	104	128	160	4.0
Other Central/South America	81	104	105	146	188	226	267	4.5
Total Developing	**674**	**942**	**968**	**1,303**	**1,658**	**2,091**	**2,573**	**4.8**
Total World	**2,482**	**2,673**	**2,712**	**3,297**	**3,863**	**4,520**	**5,218**	**3.2**

[a] Includes the 50 States and the District of Columbia. U.S. Territories are included in Australasia.

Notes: EE/FSU = Eastern Europe/Former Soviet Union.

Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 1999*, DOE/EIA-0219(99) (Washingtor DC, February 2001). **Projections:** EIA, *Annual Energy Outlook 2002*, DOE/EIA-0383(2002) (Washington, DC, December 2001) Table B19; and World Energy Projection System (2002).

added together and are projected to grow, especially in Asia, due to increased total energy consumption.

5.7. Problems and Review Questions

5.1. The world price of crude oil remained stable for about 100 years, until 1973. What were the causes of the sudden change?

5.2. Use the information in Tables 5.3 and 5.5 to list, in order, the world's ten largest producers and consumers of petroleum products, in 2000.

5.3. In Fig. 5.6, why is the characteristic for all oil consumption in Asia-Pacific growing so rapidly compared with other areas of the world?

5.4. In which countries of the world has yearly oil consumption increased most rapidly since 1990?

5.5. In which countries of the world has the average annual oil production increased most rapidly since 1990?

5.6. The Sultan of Brunei is reputed to be the world's richest man. What is the source of his wealth?

5.7. What are the world's busiest shipping routes for oil tankers and supertankers?

5.8. Most of the oil exported from the Middle East is transported in supertankers through the Straits of Hormuz [1].

   (a) How much oil was shipped through the Straits in 1999?
   (b) What effect would closure of the Straits of Hormuz have on the world economy if the closure lasted for (i) three months, (ii) three years?

5.9. If an oil supertanker can transport 200,000 tonnes of crude oil per journey, how many tanker journeys would have been needed to supply the entire USA oil import figure for the year 2000?

5.10. What were the values of UK petroleum exports in 1980, 1990, 2000 for (a) crude oil, (b) refined petroleum products and process oils, (c) totals for petroleum?

5.11. Repeat Problem 5.10 with respect to UK petroleum imports.

5.12. Use the results of Problems 5.10 and 5.11 to calculate the net profit on the UK foreign trade in petroleum exports and imports, comparing 1970 with 2000.

5.13. What countries were the USA's biggest oil suppliers in 2000?

5.14. In the USA, oil consumption has grown steadily. In what year did the oil deficit first exceed the oil production?

5.15. Why do the North Americans have such a large per capita consumption of oil compared with the rest of the world?

5.16. Briefly speculate on the civil, political and global consequences which could conceivably arise if oil supplies to the West were (a) suddenly interrupted, (b) squeezed, forcing large price increases.

5.17. The total world consumption of oil has increased steadily since 1985. In spite of this, the years of reserves remaining have risen significantly in the same period. Why is this so?

5.18. The "years of oil reserves remaining", at present, are given in Fig. 5.4. For Western Europe the figures show less than ten years of reserves. What measures, if any, would you wish to see implemented in the light of this information?

5.19. In view of the impending shortfall of world oil supplies, what long-term plans should be considered?

5.20. What might be some of the effects on world oil consumption if the USA became politically isolationist and declared itself self-sufficient in energy?

5.21. Describe some of the difficulties that would be experienced in extracting and refining crude oil from oil shale and tar sands.

5.22. Oil extraction and refining is responsible for almost as much carbon emission as coal and natural gas together. Yet coal is thought to be a "dirty" fuel and oil has a relatively "clean" image. Why is this so?

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CHAPTER 6

NATURAL GAS

6.1. Introduction

Naturally occurring gas or natural gas is a mixture of hydrocarbon and non-hydrocarbon gases but is mostly methane (CH_4). Many natural gas deposits occur independently of oil deposits and are then sometimes called “non-associated” (with oil) deposits. Non-associated gas is derived from organic matter (often coal) by the thermal degradation and the natural degasification of coal strata deposited at greater depths and increasing geological temperature. The deposits of natural gas that occur in association with oil accumulations, either as a separate gas layer or in solution, are sometimes called “associated gas” or “condensate”. In the early days of oil exploration, the fuel value of the associated gas was not always appreciated. Sometimes it was flared off by burning, a practice still widely used in the Middle East, and thereby wasted. In a modern petrochemical plant in Europe or North America a burning gas flare is likely to be a temporary safety feature.

The synthetic gas that used to be called “coal gas” or “town gas” is obtained by the industrial processing of coal and is described in Sec. 6.8. Coal gas and natural gas are used in the same applications but are entirely different in origin and differ in composition.

In addition to methane, which is usually between 85% and 95% of the content, natural gas also contains the hydrocarbons ethane, propane, butane and pentane (short carbon chain paraffins), plus non-hydrocarbons including nitrogen, hydrogen sulphide and carbon dioxide. The precise composition depends on the particular source and nature of the gas. The “dry” natural gas sold as gaseous fossil fuel contains about 96% methane, 5.3% propane and 2.6% butane. Butane and propane may be liquefied and sold as liquid petroleum gases such as “calogas” [1]. Natural gas itself can be liquefied by refrigeration and is then known as liquid natural gas (LNG) in North America or natural gas liquid (NGL) or condensate in Europe.

Natural gas is measured by volume (not by weight) in the volumetric units of cubic feet or cubic metres. Slightly inconsistent conversion factors exist due to the different grades of fuel. A cubic foot is the energy equivalent of 1000 BTU or 1.05 MJ. One cubic metre has an equivalent heat energy of 1000 kcal or 3.77×10^7 J [2]. In volumetric terms it is convenient to measure industrial quantities of gas in millions (10^6), US billions (10^9) or trillions (10^{12}) of cubic feet or cubic metres. For direct comparison with the fuel energy properties of coal or oil, the large-scale use of gas can be measured in million tonnes of oil equivalent (mtoe).

6.2. History and Development

In the 19th century the discovery and development of natural gas as a fuel first proceeded concurrently in the USA and in imperial Russia. The first natural gas pipeline, 22 km long, transported gas to Pittsburgh, USA, in 1883. During the same period the development of both oil and natural gas occurred in the Baku oilfield near the Caspian Sea in the (then) pre-Soviet Czarist Russia [3].

The exploitation of natural gas as a fuel was dominated by the USA until the 1950s. In 1950 over 85% of the world's natural gas was produced and consumed in the USA, with Venezuela and Russia exploiting 8% and 4%, respectively. It was not until August 1959 that the first major giant Groningen gas field discovery was made in Holland by a joint Esso–Shell team. The North Sea between Great Britain and continental Europe has proved to contain deep buried coal layers lying underneath porous sandstone and sealed by a thick impermeable cap-rock. Natural gas was generated from these coals and has permeated into the sandstone. Countries with coastlines on the North Sea have agreed on defined areas of exploration and natural gas is being produced by Belgium, Denmark, Germany, the Netherlands, Norway and the UK. For example, the British Petroleum Company found gas 45 miles east of the Humber estuary in 1965 [1].

Since the early 1960s the countries of Eastern Europe have made massive increases in their exploitation and export of natural gas.

6.3. Natural Gas Reserves

The known reserves of natural gas, shown in Figs. 6.1, 6.2 and Table 6.1, are widely distributed across the world [2]. Although the former Soviet Union has almost 40% of the known reserves and Iran 15%, Table 6.1, there are many countries with worthwhile reserves. Further information on area reserves and the changes over the past 25 years are shown in Fig. 6.2. Global reserves are now slowly increasing as the revised reserve estimates exceed demand. The term "proven reserves" is used to indicate the known and extractable deposits. It is significant to note that the future supply situation will not depend on a limited number of major sources. Natural gas supply is relatively easy to transport, via pipelines, compared with coal and crude oil.

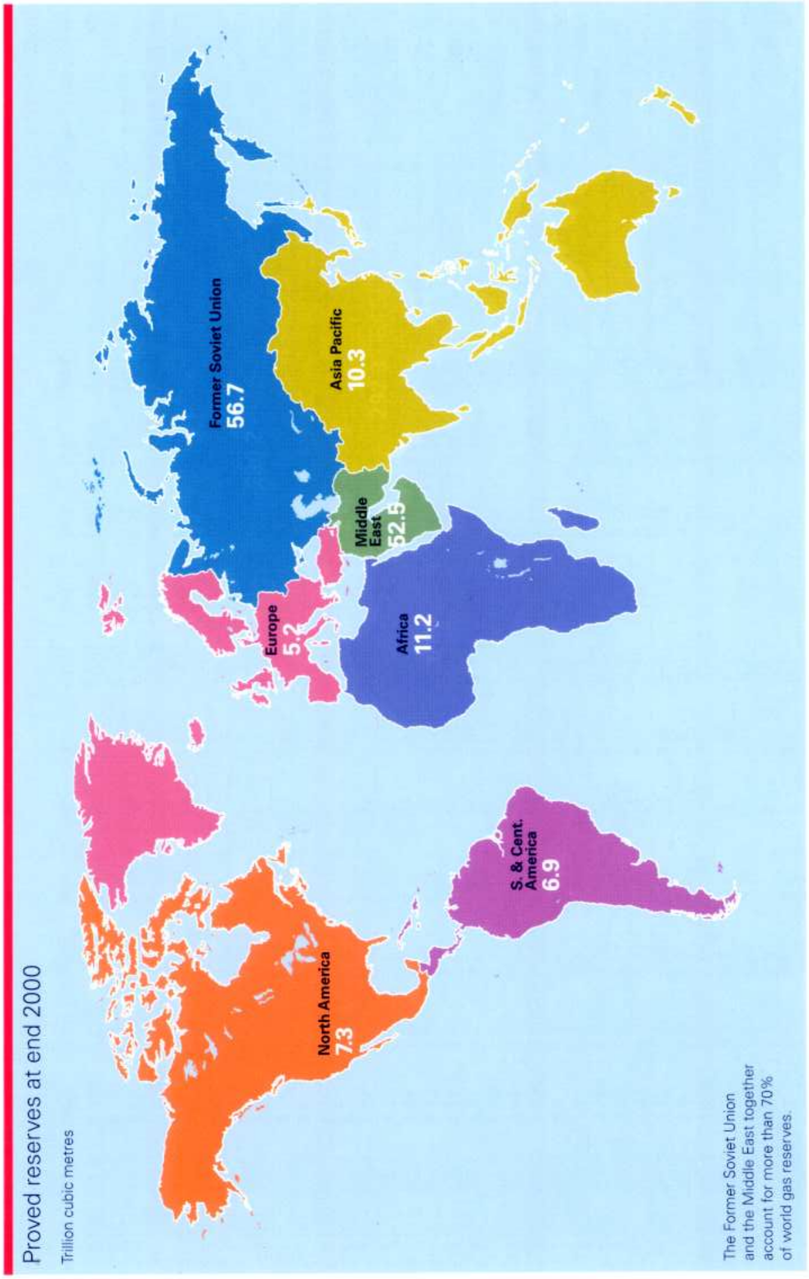

Proved reserves at end 2000
Trillion cubic metres
North America
7.3
S. & Cent. America
6.9
Europe
5.2
Former Soviet Union
56.7
Africa
11.2
Middle East
52.5
Asia Pacific
10.3
The Former Soviet Union and the Middle East together account for more than 70% of world gas reserves.

Fig. 6.1. World reserves of natural gas, by region, 2000 [2].

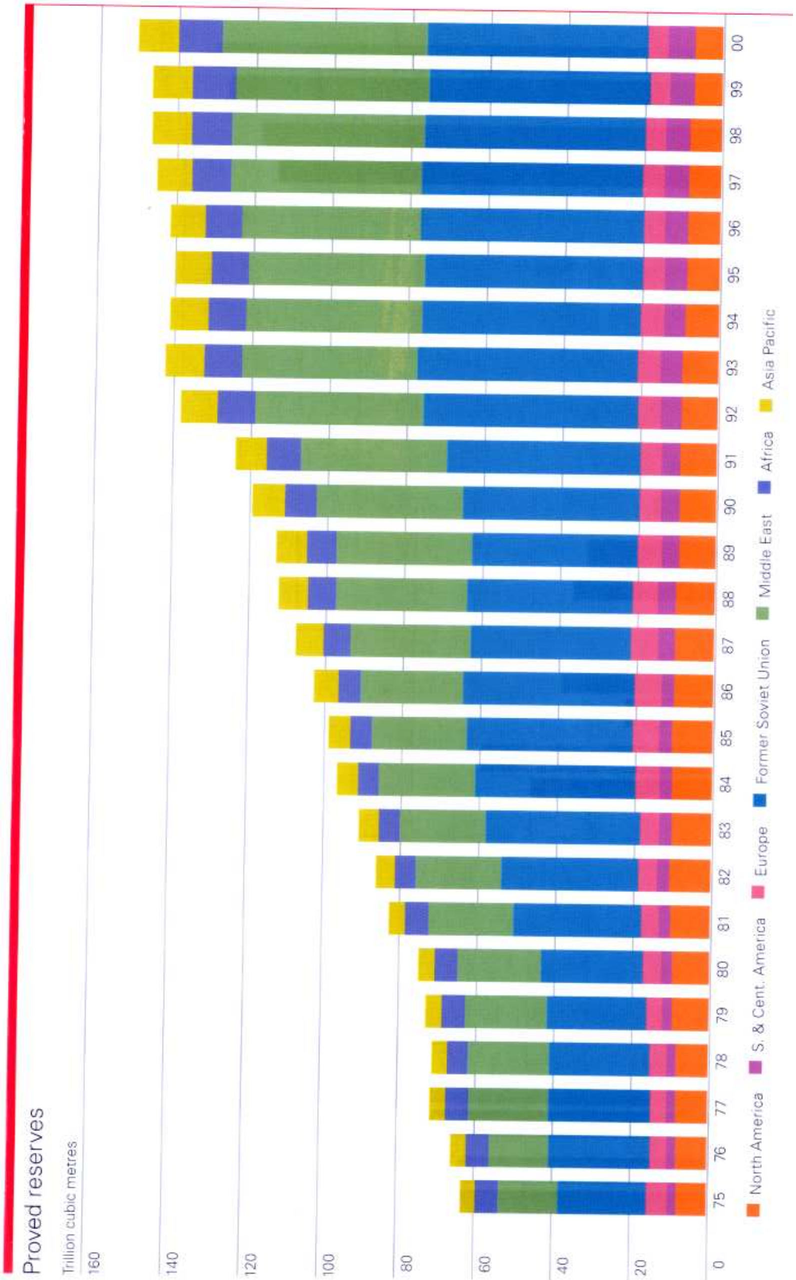
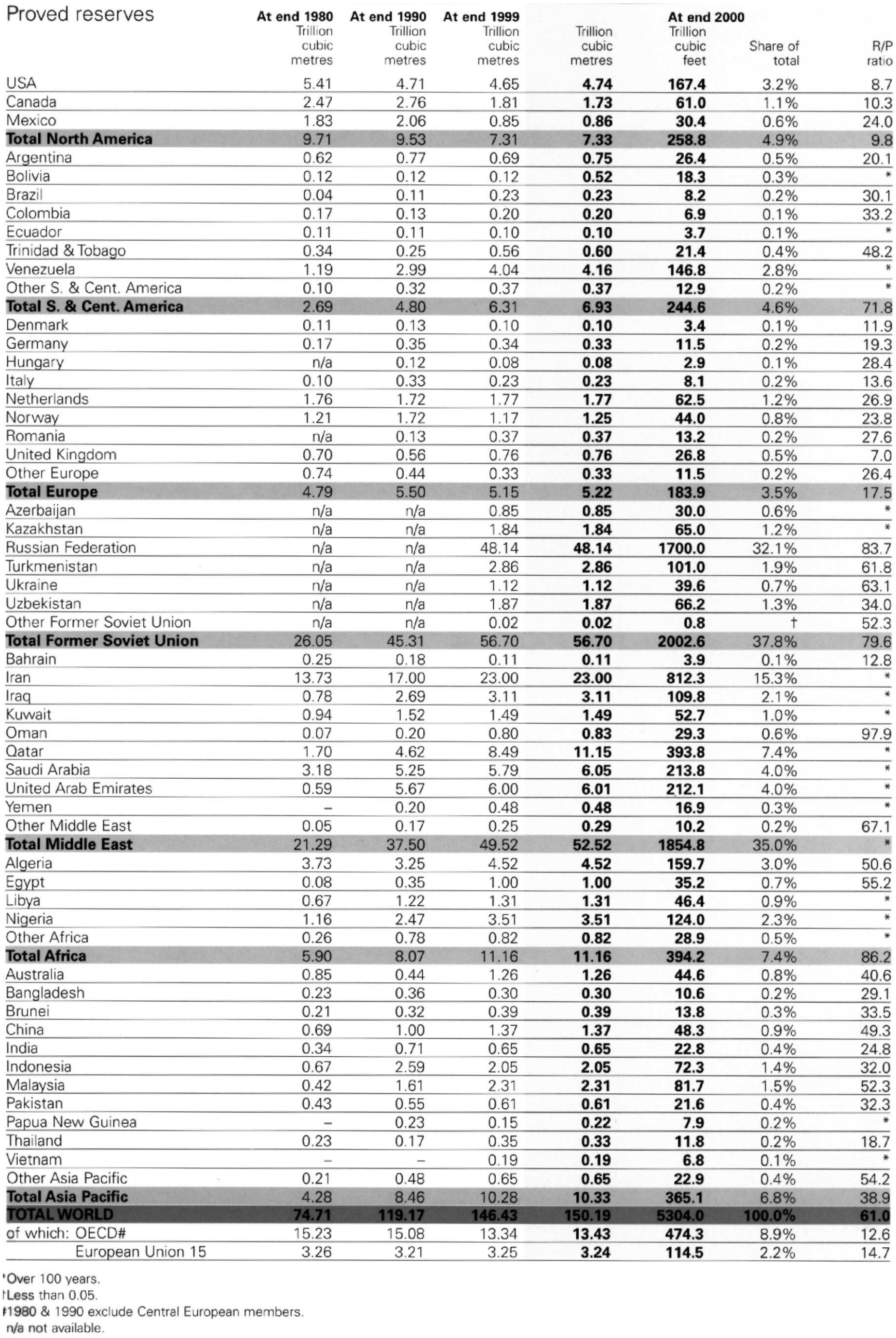


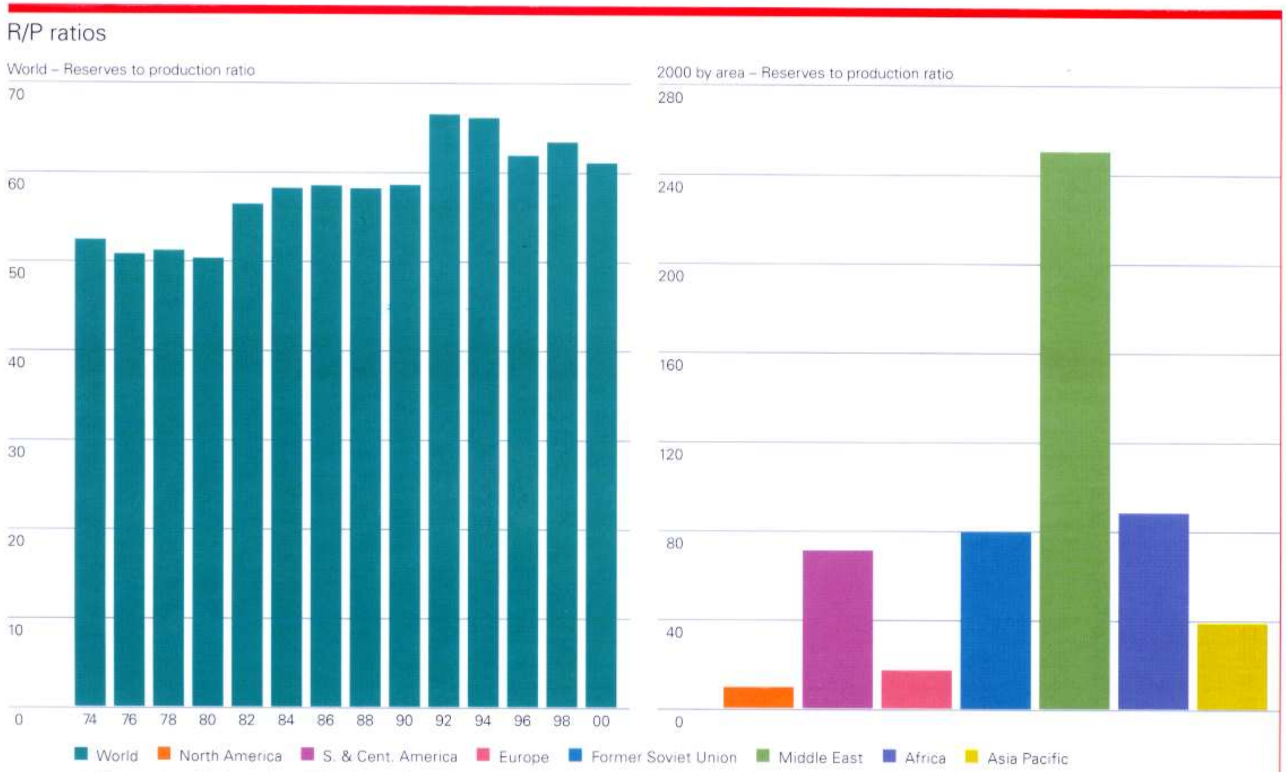
Fig. 6.2. World reserves of natural gas by year and by region, 1975–2000 [2].

Table 6.1. World natural gas reserves [2].



Proved reserves	At end 1980 Trillion cubic metres	At end 1990 Trillion cubic metres	At end 1999 Trillion cubic metres	At end 2000 Trillion cubic metres	At end 2000 Trillion cubic feet	At end 2000 Share of total	At end 2000 R/P ratio
USA	5.41	4.71	4.65	**4.74**	**167.4**	3.2%	8.7
Canada	2.47	2.76	1.81	**1.73**	**61.0**	1.1%	10.3
Mexico	1.83	2.06	0.85	**0.86**	**30.4**	0.6%	24.0
Total North America	9.71	9.53	7.31	**7.33**	**258.8**	4.9%	9.8
Argentina	0.62	0.77	0.69	**0.75**	**26.4**	0.5%	20.1
Bolivia	0.12	0.12	0.12	**0.52**	**18.3**	0.3%	*
Brazil	0.04	0.11	0.23	**0.23**	**8.2**	0.2%	30.1
Colombia	0.17	0.13	0.20	**0.20**	**6.9**	0.1%	33.2
Ecuador	0.11	0.11	0.10	**0.10**	**3.7**	0.1%	*
Trinidad & Tobago	0.34	0.25	0.56	**0.60**	**21.4**	0.4%	48.2
Venezuela	1.19	2.99	4.04	**4.16**	**146.8**	2.8%	*
Other S. & Cent. America	0.10	0.32	0.37	**0.37**	**12.9**	0.2%	*
Total S. & Cent. America	2.69	4.80	6.31	**6.93**	**244.6**	4.6%	71.8
Denmark	0.11	0.13	0.10	**0.10**	**3.4**	0.1%	11.9
Germany	0.17	0.35	0.34	**0.33**	**11.5**	0.2%	19.3
Hungary	n/a	0.12	0.08	**0.08**	**2.9**	0.1%	28.4
Italy	0.10	0.33	0.23	**0.23**	**8.1**	0.2%	13.6
Netherlands	1.76	1.72	1.77	**1.77**	**62.5**	1.2%	26.9
Norway	1.21	1.72	1.17	**1.25**	**44.0**	0.8%	23.8
Romania	n/a	0.13	0.37	**0.37**	**13.2**	0.2%	27.6
United Kingdom	0.70	0.56	0.76	**0.76**	**26.8**	0.5%	7.0
Other Europe	0.74	0.44	0.33	**0.33**	**11.5**	0.2%	26.4
Total Europe	4.79	5.50	5.15	**5.22**	**183.9**	3.5%	17.5
Azerbaijan	n/a	n/a	0.85	**0.85**	**30.0**	0.6%	*
Kazakhstan	n/a	n/a	1.84	**1.84**	**65.0**	1.2%	*
Russian Federation	n/a	n/a	48.14	**48.14**	**1700.0**	32.1%	83.7
Turkmenistan	n/a	n/a	2.86	**2.86**	**101.0**	1.9%	61.8
Ukraine	n/a	n/a	1.12	**1.12**	**39.6**	0.7%	63.1
Uzbekistan	n/a	n/a	1.87	**1.87**	**66.2**	1.3%	34.0
Other Former Soviet Union	n/a	n/a	0.02	**0.02**	**0.8**	†	52.3
Total Former Soviet Union	26.05	45.31	56.70	**56.70**	**2002.6**	37.8%	79.6
Bahrain	0.25	0.18	0.11	**0.11**	**3.9**	0.1%	12.8
Iran	13.73	17.00	23.00	**23.00**	**812.3**	15.3%	*
Iraq	0.78	2.69	3.11	**3.11**	**109.8**	2.1%	*
Kuwait	0.94	1.52	1.49	**1.49**	**52.7**	1.0%	*
Oman	0.07	0.20	0.80	**0.83**	**29.3**	0.6%	97.9
Qatar	1.70	4.62	8.49	**11.15**	**393.8**	7.4%	*
Saudi Arabia	3.18	5.25	5.79	**6.05**	**213.8**	4.0%	*
United Arab Emirates	0.59	5.67	6.00	**6.01**	**212.1**	4.0%	*
Yemen	–	0.20	0.48	**0.48**	**16.9**	0.3%	*
Other Middle East	0.05	0.17	0.25	**0.29**	**10.2**	0.2%	67.1
Total Middle East	21.29	37.50	49.52	**52.52**	**1854.8**	35.0%	*
Algeria	3.73	3.25	4.52	**4.52**	**159.7**	3.0%	50.6
Egypt	0.08	0.35	1.00	**1.00**	**35.2**	0.7%	55.2
Libya	0.67	1.22	1.31	**1.31**	**46.4**	0.9%	*
Nigeria	1.16	2.47	3.51	**3.51**	**124.0**	2.3%	*
Other Africa	0.26	0.78	0.82	**0.82**	**28.9**	0.5%	*
Total Africa	5.90	8.07	11.16	**11.16**	**394.2**	7.4%	86.2
Australia	0.85	0.44	1.26	**1.26**	**44.6**	0.8%	40.6
Bangladesh	0.23	0.36	0.30	**0.30**	**10.6**	0.2%	29.1
Brunei	0.21	0.32	0.39	**0.39**	**13.8**	0.3%	33.5
China	0.69	1.00	1.37	**1.37**	**48.3**	0.9%	49.3
India	0.34	0.71	0.65	**0.65**	**22.8**	0.4%	24.8
Indonesia	0.67	2.59	2.05	**2.05**	**72.3**	1.4%	32.0
Malaysia	0.42	1.61	2.31	**2.31**	**81.7**	1.5%	52.3
Pakistan	0.43	0.55	0.61	**0.61**	**21.6**	0.4%	32.3
Papua New Guinea	–	0.23	0.15	**0.22**	**7.9**	0.2%	*
Thailand	0.23	0.17	0.35	**0.33**	**11.8**	0.2%	18.7
Vietnam	–	–	0.19	**0.19**	**6.8**	0.1%	*
Other Asia Pacific	0.21	0.48	0.65	**0.65**	**22.9**	0.4%	54.2
Total Asia Pacific	4.28	8.46	10.28	**10.33**	**365.1**	6.8%	38.9
TOTAL WORLD	**74.71**	**119.17**	**146.43**	**150.19**	**5304.0**	**100.0%**	**61.0**
of which: OECD#	15.23	15.08	13.34	**13.43**	**474.3**	8.9%	12.6
European Union 15	3.26	3.21	3.25	**3.24**	**114.5**	2.2%	14.7

*Over 100 years.
†Less than 0.05.
#1980 & 1990 exclude Central European members.
n/a not available.



At 61 years, the global natural gas R/P ratio remains well above that for oil, despite a continuation of the decline since 1993. R/P ratios are lowest in the well-developed markets of North America and Europe, and highest in the resource-rich regions of the Middle East, Former Soviet Union and Africa.

Fig. 6.3. Natural gas reserve/production (R/P) ratios since 1974 [2].

By the use of reserve/production (R/P) ratios, the reserves can be calculated in terms of "years of reserves remaining". This information is presented graphically in Fig. 6.3. Estimated world reserves have decreased steadily since the early 1990s because increased usage has exceeded new discoveries and revised estimates of reserves. Comparison of Fig. 6.3 with the corresponding Fig. 5.4 for oil shows that the situation regarding gas reserves is similar to that regarding oil reserves. For both oil and natural gas the world's biggest repository for reserves is the Middle East, where the gas accumulations are largely untouched because of the much greater profitability of oil.

The world natural gas supply will outlast the oil by about a generation. As with oil, it would be risky to assume that the reserve figures will continue to rise. This is particularly pertinent to the OECD countries where the reserve figure has remained low and roughly constant since the early 1970s, and is now (2002) starting to decrease.

All of the concerns regarding world oil reserves, discussed in Chapter 5, also apply to natural gas. The world consumption of natural gas was only slightly more than one-half that of oil but in 2000 constituted 24.7% of the world total primary fuel consumption. The depletion of the world stock of natural gas, like that of oil, is a world problem.

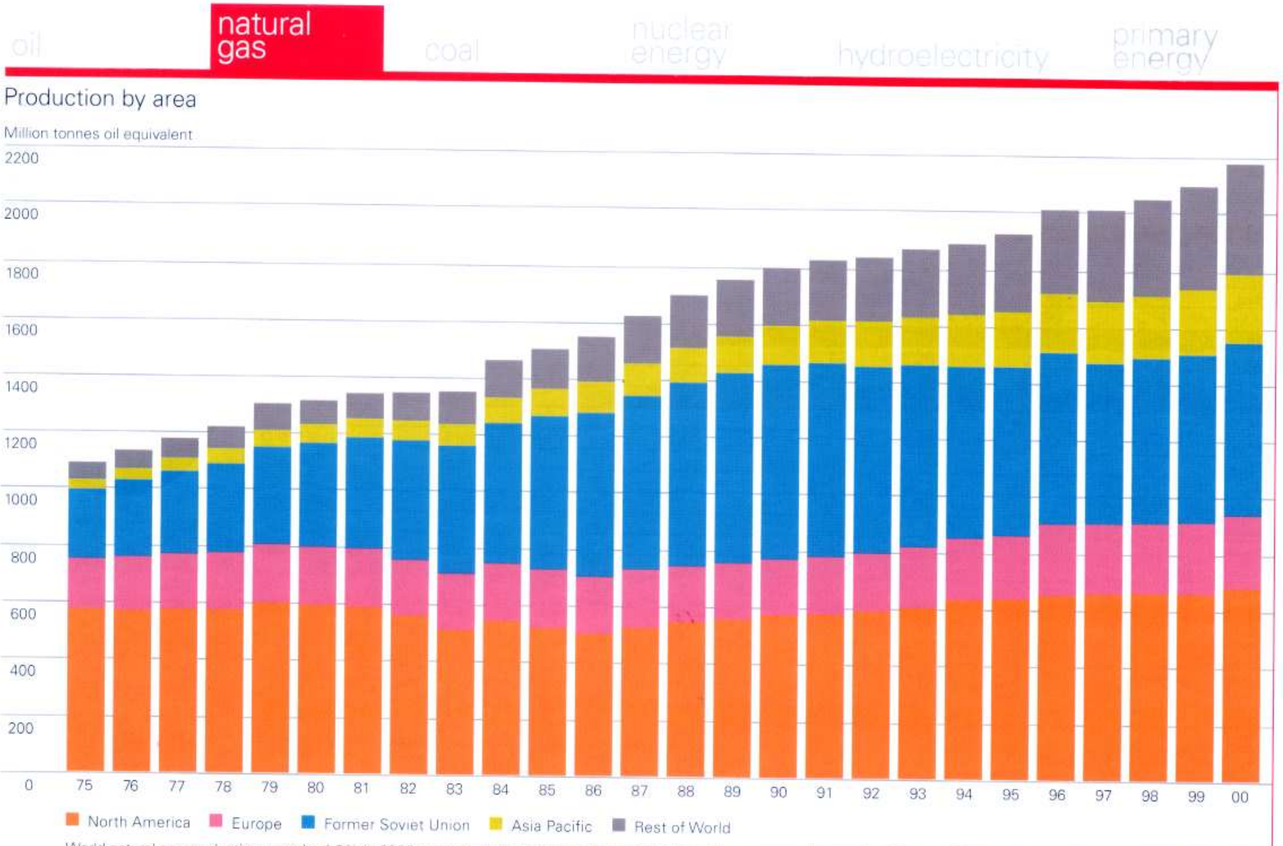
6.4. Production and Consumption of Natural Gas

6.4.1. *World natural gas production*

Natural gas is produced and consumed all over the world. Moreover, the proportion of total world primary energy consumption taken up by natural gas is projected to significantly increase in future energy demand. The relative production in different areas of the world is shown in Fig. 6.4, with much detail for the past 11 years given in Table 6.2. World production has increased steadily, so as to double in the past 25 years, for all regions except the former Soviet Union. In the 11 years 1990–2000 production increased in the order of 15–20% in Western Europe and North America but doubled in the Middle East, Asia and Africa. In the UK there has been an increase in production of about 80% since 1985. In 1996 Britain became the biggest gas market in Europe.

6.4.2. *World natural gas consumption*

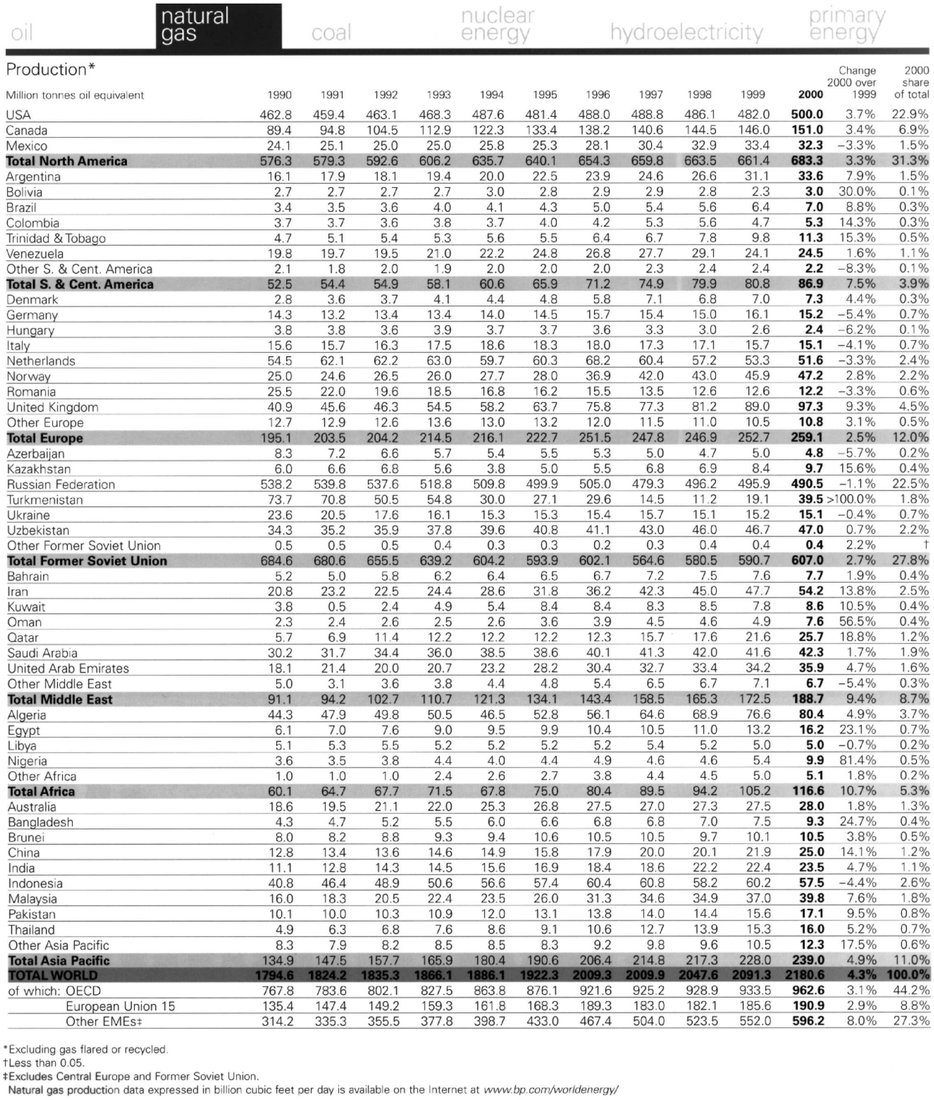
The production and consumption of natural gas for different areas of the world, Figs. 6.4 and 6.5, both show a steady increase. This is projected to continue, Fig. 6.6 [4, 5]. There has been a reduction of use in Eastern Europe since 1990, which is now recovering. This is also the case with oil. Detailed figures for natural gas consumption for the years 1990–2000 are given in Table 6.3. Comparison between the



World natural gas production grew by 4.3% in 2000, more than double the average rate of growth experienced in the last 10 years. Production increased in all regions, with the **fastest growth** in the Middle East and Africa.

Fig. 6.4. Natural gas production, by area, 1975–2000 [2].

Table 6.2. Natural gas production since 1990, by country and by year [2].



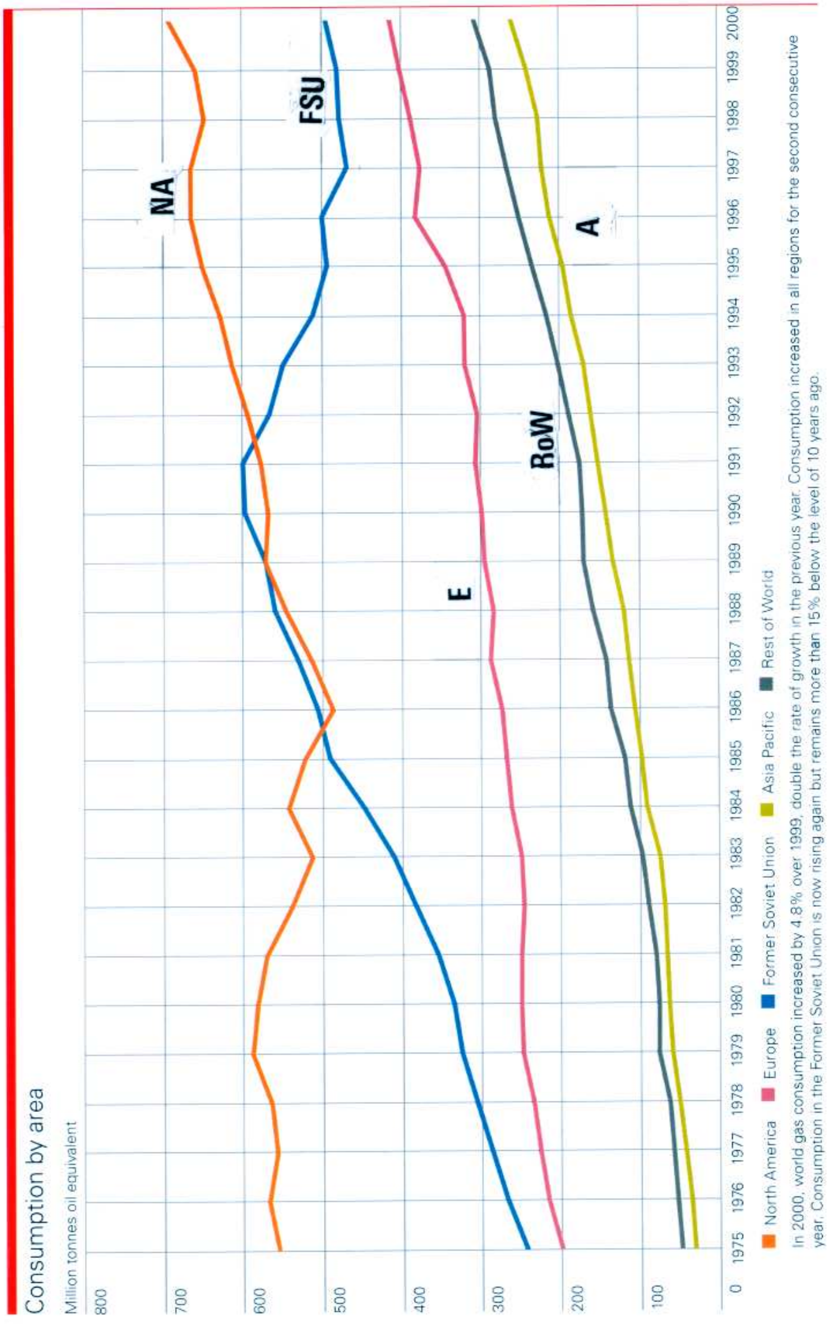
oil
natural gas
coal
nuclear energy
hydroelectricity
primary energy

Production*

Million tonnes oil equivalent	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	**2000**	Change 2000 over 1999	2000 share of total
USA	462.8	459.4	463.1	468.3	487.6	481.4	488.0	488.8	486.1	482.0	**500.0**	3.7%	22.9%
Canada	89.4	94.8	104.5	112.9	122.3	133.4	138.2	140.6	144.5	146.0	**151.0**	3.4%	6.9%
Mexico	24.1	25.1	25.0	25.0	25.8	25.3	28.1	30.4	32.9	33.4	**32.3**	−3.3%	1.5%
Total North America	576.3	579.3	592.6	606.2	635.7	640.1	654.3	659.8	663.5	661.4	**683.3**	3.3%	31.3%
Argentina	16.1	17.9	18.1	19.4	20.0	22.5	23.9	24.6	26.6	31.1	**33.6**	7.9%	1.5%
Bolivia	2.7	2.7	2.7	2.7	3.0	2.8	2.9	2.9	2.8	2.3	**3.0**	30.0%	0.1%
Brazil	3.4	3.5	3.6	4.0	4.1	4.3	5.0	5.4	5.6	6.4	**7.0**	8.8%	0.3%
Colombia	3.7	3.7	3.6	3.8	3.7	4.0	4.2	5.3	5.6	4.7	**5.3**	14.3%	0.3%
Trinidad & Tobago	4.7	5.1	5.4	5.3	5.6	5.5	6.4	6.7	7.8	9.8	**11.3**	15.3%	0.5%
Venezuela	19.8	19.7	19.5	21.0	22.2	24.8	26.8	27.7	29.1	24.1	**24.5**	1.6%	1.1%
Other S. & Cent. America	2.1	1.8	2.0	1.9	2.0	2.0	2.0	2.3	2.4	2.4	**2.2**	−8.3%	0.1%
Total S. & Cent. America	52.5	54.4	54.9	58.1	60.6	65.9	71.2	74.9	79.9	80.8	**86.9**	7.5%	3.9%
Denmark	2.8	3.6	3.7	4.1	4.4	4.8	5.8	7.1	6.8	7.0	**7.3**	4.4%	0.3%
Germany	14.3	13.2	13.4	13.4	14.0	14.5	15.7	15.4	15.0	16.1	**15.2**	−5.4%	0.7%
Hungary	3.8	3.8	3.6	3.9	3.7	3.7	3.6	3.3	3.0	2.6	**2.4**	−6.2%	0.1%
Italy	15.6	15.7	16.3	17.5	18.6	18.3	18.0	17.3	17.1	15.7	**15.1**	−4.1%	0.7%
Netherlands	54.5	62.1	62.2	63.0	59.7	60.3	68.2	60.4	57.2	53.3	**51.6**	−3.3%	2.4%
Norway	25.0	24.6	26.5	26.0	27.7	28.0	36.9	42.0	43.0	45.9	**47.2**	2.8%	2.2%
Romania	25.5	22.0	19.6	18.5	16.8	16.2	15.5	13.5	12.6	12.6	**12.2**	−3.3%	0.6%
United Kingdom	40.9	45.6	46.3	54.5	58.2	63.7	75.8	77.3	81.2	89.0	**97.3**	9.3%	4.5%
Other Europe	12.7	12.9	12.6	13.6	13.0	13.2	12.0	11.5	11.0	10.5	**10.8**	3.1%	0.5%
Total Europe	195.1	203.5	204.2	214.5	216.1	222.7	251.5	247.8	246.9	252.7	**259.1**	2.5%	12.0%
Azerbaijan	8.3	7.2	6.6	5.7	5.4	5.5	5.3	5.0	4.7	5.0	**4.8**	−5.7%	0.2%
Kazakhstan	6.0	6.6	6.8	5.6	3.8	5.0	5.5	6.8	6.9	8.4	**9.7**	15.6%	0.4%
Russian Federation	538.2	539.8	537.6	518.8	509.8	499.9	505.0	479.3	496.2	495.9	**490.5**	−1.1%	22.5%
Turkmenistan	73.7	70.8	50.5	54.8	30.0	27.1	29.6	14.5	11.2	19.1	**39.5**	>100.0%	1.8%
Ukraine	23.6	20.5	17.6	16.1	15.3	15.3	15.4	15.7	15.1	15.2	**15.1**	−0.4%	0.7%
Uzbekistan	34.3	35.2	35.9	37.8	39.6	40.8	41.1	43.0	46.0	46.7	**47.0**	0.7%	2.2%
Other Former Soviet Union	0.5	0.5	0.5	0.4	0.3	0.3	0.2	0.3	0.4	0.4	**0.4**	2.2%	†
Total Former Soviet Union	684.6	680.6	655.5	639.2	604.2	593.9	602.1	564.6	580.5	590.7	**607.0**	2.7%	27.8%
Bahrain	5.2	5.0	5.8	6.2	6.4	6.5	6.7	7.2	7.5	7.6	**7.7**	1.9%	0.4%
Iran	20.8	23.2	22.5	24.4	28.6	31.8	36.2	42.3	45.0	47.7	**54.2**	13.8%	2.5%
Kuwait	3.8	0.5	2.4	4.9	5.4	8.4	8.4	8.3	8.5	7.8	**8.6**	10.5%	0.4%
Oman	2.3	2.4	2.6	2.5	2.6	3.6	3.9	4.5	4.6	4.9	**7.6**	56.5%	0.4%
Qatar	5.7	6.9	11.4	12.2	12.2	12.2	12.3	15.7	17.6	21.6	**25.7**	18.8%	1.2%
Saudi Arabia	30.2	31.7	34.4	36.0	38.5	38.6	40.1	41.3	42.0	41.6	**42.3**	1.7%	1.9%
United Arab Emirates	18.1	21.4	20.0	20.7	23.2	28.2	30.4	32.7	33.4	34.2	**35.9**	4.7%	1.6%
Other Middle East	5.0	3.1	3.6	3.8	4.4	4.8	5.4	6.5	6.7	7.1	**6.7**	−5.4%	0.3%
Total Middle East	91.1	94.2	102.7	110.7	121.3	134.1	143.4	158.5	165.3	172.5	**188.7**	9.4%	8.7%
Algeria	44.3	47.9	49.8	50.5	46.5	52.8	56.1	64.6	68.9	76.6	**80.4**	4.9%	3.7%
Egypt	6.1	7.0	7.6	9.0	9.5	9.9	10.4	10.5	11.0	13.2	**16.2**	23.1%	0.7%
Libya	5.1	5.3	5.5	5.2	5.2	5.2	5.2	5.4	5.2	5.0	**5.0**	−0.7%	0.2%
Nigeria	3.6	3.5	3.8	4.4	4.0	4.4	4.9	4.6	4.6	5.4	**9.9**	81.4%	0.5%
Other Africa	1.0	1.0	1.0	2.4	2.6	2.7	3.8	4.4	4.5	5.0	**5.1**	1.8%	0.2%
Total Africa	60.1	64.7	67.7	71.5	67.8	75.0	80.4	89.5	94.2	105.2	**116.6**	10.7%	5.3%
Australia	18.6	19.5	21.1	22.0	25.3	26.8	27.5	27.0	27.3	27.5	**28.0**	1.8%	1.3%
Bangladesh	4.3	4.7	5.2	5.5	6.0	6.6	6.8	6.8	7.0	7.5	**9.3**	24.7%	0.4%
Brunei	8.0	8.2	8.8	9.3	9.4	10.6	10.5	10.5	9.7	10.1	**10.5**	3.8%	0.5%
China	12.8	13.4	13.6	14.6	14.9	15.8	17.9	20.0	20.1	21.9	**25.0**	14.1%	1.2%
India	11.1	12.8	14.3	14.5	15.6	16.9	18.4	18.6	22.2	22.4	**23.5**	4.7%	1.1%
Indonesia	40.8	46.4	48.9	50.6	56.6	57.4	60.4	60.8	58.2	60.2	**57.5**	−4.4%	2.6%
Malaysia	16.0	18.3	20.5	22.4	23.5	26.0	31.3	34.6	34.9	37.0	**39.8**	7.6%	1.8%
Pakistan	10.1	10.0	10.3	10.9	12.0	13.1	13.8	14.0	14.4	15.6	**17.1**	9.5%	0.8%
Thailand	4.9	6.3	6.8	7.6	8.6	9.1	10.6	12.7	13.9	15.3	**16.0**	5.2%	0.7%
Other Asia Pacific	8.3	7.9	8.2	8.5	8.5	8.3	9.2	9.8	9.6	10.5	**12.3**	17.5%	0.6%
Total Asia Pacific	134.9	147.5	157.7	165.9	180.4	190.6	206.4	214.8	217.3	228.0	**239.0**	4.9%	11.0%
TOTAL WORLD	**1794.6**	**1824.2**	**1835.3**	**1866.1**	**1886.1**	**1922.3**	**2009.3**	**2009.9**	**2047.6**	**2091.3**	**2180.6**	**4.3%**	**100.0%**
of which: OECD	767.8	783.6	802.1	827.5	863.8	876.1	921.6	925.2	928.9	933.5	**962.6**	3.1%	44.2%
European Union 15	135.4	147.4	149.2	159.3	161.8	168.3	189.3	183.0	182.1	185.6	**190.9**	2.9%	8.8%
Other EMEs‡	314.2	335.3	355.5	377.8	398.7	433.0	467.4	504.0	523.5	552.0	**596.2**	8.0%	27.3%

*Excluding gas flared or recycled.
†Less than 0.05.
‡Excludes Central Europe and Former Soviet Union.
Natural gas production data expressed in billion cubic feet per day is available on the Internet at *www.bp.com/worldenergy/*

production and consumption figures in Tables 6.2 and 6.3, respectively, shows that the Russian Federation, Algeria, Canada, Indonesia, the Netherlands and Norway are net exporter countries while France, Germany, Italy, Japan and the USA are importer countries. The trade flow of natural gas implied in the data of Tables 6.2 and 6.3 is illustrated in Fig. 6.7. In Western Europe natural gas has now overtaken coal as the second most important fuel, after oil. The stable price of natural gas over the last ten years is illustrated in Table 6.4, although it has doubled in North America since 1998.



In 2000, world gas consumption increased by 4.8% over 1999, double the rate of growth in the previous year. Consumption increased in all regions for the second consecutive year. Consumption in the Former Soviet Union is now rising again but remains more than 15% below the level of 10 years ago.

Fig. 6.5. Natural gas consumption since 1975, by region [2].

Table 6.3. Natural gas consumption, by country and by year, since 1990 [2].

Consumption

Million tonnes oil equivalent	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	**2000**	Change 2000 over 1999	2000 share of total
USA	486.3	494.1	507.3	524.9	536.5	558.5	568.5	567.8	552.4	561.7	**588.9**	4.8%	27.2%
Canada	55.6	56.7	60.2	61.6	63.8	63.8	66.9	67.3	63.3	65.4	**70.1**	7.1%	3.2%
Mexico	25.0	24.9	24.9	25.4	26.5	26.7	27.9	28.5	30.9	30.6	**32.0**	4.6%	1.5%
Total North America	566.9	575.7	592.4	611.9	626.8	649.0	663.3	663.6	646.6	657.7	**691.0**	5.1%	31.9%
Argentina	18.3	19.9	20.1	21.2	21.9	24.3	25.7	25.7	27.5	30.4	**29.8**	–1.9%	1.4%
Brazil	3.4	3.5	3.6	4.0	4.1	4.3	5.0	5.4	5.6	6.4	**8.5**	32.7%	0.4%
Chile	1.5	1.3	1.5	1.4	1.5	1.5	1.5	2.5	2.9	3.6	**5.2**	45.0%	0.2%
Colombia	3.7	3.7	3.6	3.8	3.7	4.0	4.2	5.3	5.6	4.7	**5.3**	14.4%	0.2%
Ecuador	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	**0.1**	–	†
Peru	0.4	0.4	0.3	0.4	0.4	0.4	0.4	0.3	0.5	0.5	**0.4**	–18.4%	†
Venezuela	19.8	19.7	19.5	21.0	22.2	24.8	26.8	27.7	29.1	24.1	**24.5**	1.6%	1.1%
Other S. & Cent. America	5.4	5.8	6.1	6.1	6.5	6.5	7.4	8.0	8.9	9.3	**9.7**	3.6%	0.5%
Total S. & Cent. America	52.6	54.4	54.8	58.0	60.4	65.9	71.1	75.0	80.2	79.1	**83.5**	5.6%	3.8%
Austria	5.2	5.4	5.4	5.7	5.8	6.1	6.6	6.9	7.1	7.2	**7.1**	–1.0%	0.3%
Belgium & Luxembourg	9.5	9.0	9.0	9.9	9.7	10.6	11.8	11.3	12.4	13.3	**13.4**	0.8%	0.6%
Bulgaria	5.3	4.5	3.9	3.7	3.7	4.5	4.6	3.7	3.1	2.8	**2.8**	–1.6%	0.1%
Czech Republic	4.9	5.3	5.2	5.3	5.7	6.5	7.6	7.7	7.7	7.7	**7.7**	–0.4%	0.4%
Denmark	1.8	2.1	2.2	2.5	2.7	3.1	3.7	3.9	4.3	4.5	**4.4**	–1.9%	0.2%
Finland	2.3	2.4	2.5	2.6	2.8	2.9	3.0	2.9	3.3	3.3	**3.4**	2.2%	0.2%
France	26.4	27.5	28.3	29.0	27.8	29.6	32.5	31.2	33.3	33.9	**35.6**	5.0%	1.6%
Germany	53.9	56.6	56.7	59.8	61.1	67.0	75.2	71.3	71.7	72.1	**71.3**	–1.2%	3.3%
Greece	0.1	0.1	0.1	0.1	†	†	†	0.2	0.7	1.2	**1.5**	26.8%	0.1%
Hungary	8.7	8.6	7.4	8.1	8.4	9.2	10.2	9.7	9.8	9.9	**9.6**	–2.5%	0.4%
Iceland	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Republic of Ireland	1.9	1.9	1.9	2.2	2.2	2.3	2.7	2.8	2.8	3.0	**3.4**	14.6%	0.2%
Italy	39.1	41.5	41.1	42.1	40.8	44.9	46.4	47.9	51.5	56.0	**57.4**	2.6%	2.7%
Netherlands	31.0	34.2	33.0	34.1	33.2	34.0	37.5	35.2	34.9	34.1	**34.5**	1.0%	1.6%
Norway	1.9	2.2	2.3	2.4	2.6	2.7	2.9	3.3	3.4	3.2	**3.5**	8.3%	0.2%
Poland	8.9	7.9	7.8	8.1	8.2	8.9	9.5	9.4	9.5	9.3	**10.0**	7.5%	0.5%
Portugal	–	–	–	–	–	–	–	0.1	0.7	2.0	**5.4**	>100.0%	0.2%
Romania	27.7	22.3	22.8	22.7	21.8	21.6	21.8	18.0	16.8	15.5	**14.6**	–5.9%	0.7%
Slovakia	5.3	4.9	4.9	4.6	4.5	5.1	5.5	5.6	5.7	5.8	**5.1**	–12.0%	0.2%
Spain	5.0	5.5	5.9	5.8	6.5	7.5	8.4	11.1	11.8	13.5	**15.2**	12.0%	0.7%
Sweden	0.6	0.6	0.7	0.7	0.7	0.7	0.8	0.7	0.8	0.8	**0.8**	1.3%	†
Switzerland	1.6	1.8	1.9	2.0	2.0	2.2	2.4	2.3	2.4	2.4	**2.4**	–0.9%	0.1%
Turkey	3.0	4.0	4.1	4.5	5.9	6.2	8.1	8.5	8.9	10.8	**12.7**	17.5%	0.6%
United Kingdom	47.2	50.9	50.7	57.8	59.5	63.5	73.9	75.4	78.2	82.8	**86.1**	4.0%	4.0%
Other Europe	6.2	6.0	5.1	4.8	3.6	3.7	5.3	5.4	5.3	4.6	**5.0**	7.6%	0.2%
Total Europe	297.5	305.2	302.9	318.5	319.2	342.8	380.4	374.5	386.1	399.7	**412.9**	3.3%	19.1%
Azerbaijan	14.2	13.6	10.6	7.8	7.3	7.2	5.3	5.0	4.7	5.0	**4.9**	–3.3%	0.2%
Belarus	12.4	13.0	15.1	14.0	12.3	11.1	11.7	13.3	13.5	13.8	**14.6**	6.1%	0.7%
Kazakhstan	11.3	11.8	12.2	11.7	9.2	9.7	8.1	6.4	6.5	7.1	**7.2**	1.2%	0.3%
Lithuania	5.0	4.9	2.7	1.5	1.8	2.1	2.3	2.4	2.1	2.2	**2.4**	13.0%	0.1%
Russian Federation	378.1	388.0	375.5	374.4	351.8	340.0	341.9	315.3	328.3	326.4	**339.5**	4.0%	15.7%
Turkmenistan	8.8	8.6	8.4	8.4	9.2	7.2	9.0	9.1	9.2	10.2	**11.3**	11.6%	0.5%
Ukraine	115.0	109.3	93.2	83.6	73.2	68.6	74.2	66.8	61.9	63.6	**61.6**	–3.0%	2.9%
Uzbekistan	33.2	33.4	33.6	36.6	37.2	38.1	39.0	40.9	42.3	44.3	**44.8**	1.1%	2.1%
Other Former Soviet Union	18.5	16.4	14.1	10.0	8.4	8.2	7.1	7.9	8.3	7.1	**7.1**	1.0%	0.3%
Total Former Soviet Union	596.5	599.0	565.4	548.0	510.4	492.2	498.6	467.1	476.8	479.7	**493.4**	2.9%	22.8%
Iran	20.4	20.5	22.5	23.9	28.6	31.5	36.1	42.4	46.6	49.5	**56.6**	14.4%	2.6%
Kuwait	5.6	0.5	2.4	4.9	5.4	8.4	8.4	8.3	8.5	7.8	**8.6**	10.5%	0.4%
Qatar	5.7	6.9	11.4	12.2	12.2	12.2	12.3	13.2	13.3	14.3	**13.0**	–9.1%	0.6%
Saudi Arabia	30.2	31.7	34.4	36.0	38.5	38.6	40.1	41.3	42.0	41.6	**42.3**	1.7%	2.0%
United Arab Emirates	15.2	18.3	16.9	17.7	19.5	22.3	24.4	26.1	27.4	28.3	**30.0**	6.2%	1.4%
Other Middle East	10.7	10.4	12.0	12.5	13.4	14.5	15.6	17.7	18.4	19.1	**19.5**	1.8%	0.9%
Total Middle East	87.8	88.3	99.6	107.2	117.6	127.5	136.9	149.0	156.2	160.6	**170.0**	5.9%	7.9%
Algeria	14.5	15.3	16.0	16.7	17.6	18.9	19.3	18.1	18.8	20.0	**21.9**	9.7%	1.0%
Egypt	6.1	6.9	7.5	8.7	9.4	9.9	10.2	10.4	10.8	12.9	**16.1**	24.5%	0.7%
South Africa	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Other Africa	9.9	9.5	10.1	10.5	10.7	11.5	12.9	12.9	13.4	14.0	**14.9**	6.3%	0.7%
Total Africa	30.5	31.7	33.6	35.9	37.7	40.3	42.4	41.4	43.0	46.9	**52.9**	12.8%	2.4%
Australia	16.5	15.3	15.2	15.7	17.5	17.6	17.9	17.6	18.3	17.8	**19.1**	7.5%	0.9%
Bangladesh	4.3	4.8	5.2	5.5	6.0	6.6	6.8	6.8	7.0	7.5	**9.3**	24.7%	0.4%
China	13.2	13.4	13.6	14.6	14.9	15.9	15.9	17.4	17.4	19.3	**22.3**	16.0%	1.0%
China Hong Kong SAR	–	–	–	–	–	†	1.5	2.4	2.2	2.4	**2.2**	–9.6%	0.1%
India	11.2	12.7	14.3	14.7	15.7	17.7	18.5	19.1	20.9	21.4	**22.5**	5.2%	1.0%
Indonesia	18.0	19.5	20.3	21.5	24.6	27.0	28.2	28.7	25.0	24.8	**25.0**	0.8%	1.2%
Japan	46.1	49.2	50.4	50.7	54.3	55.0	59.5	58.6	62.5	67.1	**68.6**	2.2%	3.2%
Malaysia	6.8	8.1	9.5	11.7	12.3	12.4	14.3	15.0	15.7	17.1	**19.5**	14.0%	0.9%
New Zealand	3.8	4.2	4.4	4.3	4.0	3.7	4.3	4.6	4.0	4.7	**4.9**	4.6%	0.2%
Pakistan	10.1	10.0	10.3	10.9	12.0	13.1	13.8	14.0	14.4	15.6	**17.1**	9.5%	0.8%
Philippines	–	–	–	–	†	†	†	†	†	†	**†**	50.0%	†
Singapore	–	–	1.0	1.4	1.4	1.4	1.4	1.4	1.4	1.4	**1.4**	–	0.1%
South Korea	3.0	3.5	4.6	5.7	7.6	9.2	12.2	14.8	13.8	16.8	**18.9**	12.3%	0.9%
Taiwan	1.7	2.7	2.8	2.7	3.6	3.9	4.0	4.6	5.7	5.6	**6.2**	10.6%	0.3%
Thailand	4.9	6.3	6.8	7.6	8.6	9.0	10.7	13.1	14.3	15.6	**18.8**	20.5%	0.9%
Other Asia Pacific	2.4	2.3	2.4	2.7	2.9	3.0	3.4	3.8	4.1	4.4	**4.5**	1.4%	0.2%
Total Asia Pacific	142.0	152.0	160.8	169.7	185.4	195.5	212.4	221.9	226.7	241.5	**260.3**	7.8%	12.1%
TOTAL WORLD	**1773.8**	**1806.3**	**1809.5**	**1849.2**	**1857.5**	**1913.2**	**2005.1**	**1992.5**	**2015.6**	**2065.2**	**2164.0**	**4.8%**	**100.0%**
of which: OECD	889.3	915.4	933.2	971.0	995.8	1042.4	1100.4	1101.0	1100.4	1135.1	**1187.9**	4.6%	54.9%
European Union 15	224.0	237.7	237.5	252.3	252.8	272.2	302.5	300.9	313.5	327.7	**339.5**	3.6%	15.7%
Other EMEs‡	243.5	254.2	274.2	294.4	317.7	343.7	368.9	391.7	407.5	421.7	**455.2**	8.0%	21.0%

†Less than 0.05.
‡Excludes Central Europe and Former Soviet Union.

Note: The difference between these world consumption figures and the world production statistics on page 22 is due to variations in stocks at storage facilities and liquefaction plants, together with unavoidable disparities in the definition, measurement or conversion of gas supply and demand data.

Natural gas consumption data expressed in billion cubic feet per day is available on the Internet at *www.bp.com/worldenergy/*

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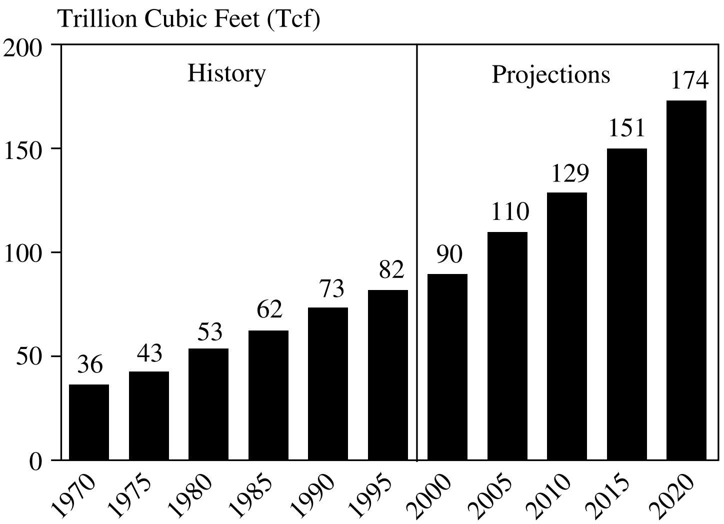


Sources: **History:** Energy Information Administration (EIA), Office of Energy Markets and End Use, International Statistics Database and *International Energy Annual 1996*, DOE/EIA-0219(96) (Washington, DC, February 1998). **Projections:** EIA, World Energy Projection System (1999).

Fig. 6.6. World natural gas consumption, 1970–2020 [4].

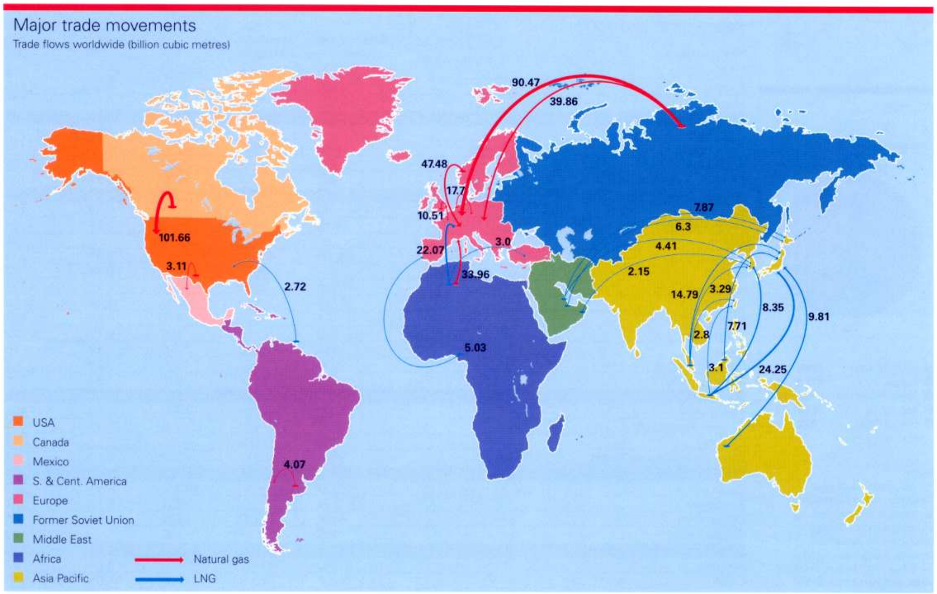

Major trade movements
Trade flows worldwide (billion cubic metres)
90.47
39.86
47.48
17.7
10.51
22.07
3.0
33.96
5.03
101.66
3.11
2.72
4.07
7.87
6.3
4.41
2.15
14.79
3.29
8.35
9.81
2.8
7.71
3.1
24.25
USA
Canada
Mexico
S. & Cent. America
Europe
Former Soviet Union
Middle East
Africa
Asia Pacific
Natural gas
LNG

Fig. 6.7. World trade movements in natural gas, 2000 [2].

Table 6.4. Natural gas prices 1985–2000 [2].

Prices	**LNG**			**Natural gas**		**Crude oil**
US dollars per million Btu	Japan cif	European Union cif	UK (Heren Index)†	USA Henry Hub‡	Canada (Alberta)‡	OECD countries cif
1985	5.23	3.83	–	–	–	4.75
1986	4.10	3.65	–	–	–	2.57
1987	3.35	2.59	–	–	–	3.09
1988	3.34	2.36	–	–	–	2.56
1989	3.28	2.09	–	1.70		3.01
1990	3.64	2.82	–	1.64	1.05	3.82
1991	3.99	3.18	–	1.49	0.89	3.33
1992	3.62	2.76	–	1.77	0.98	3.19
1993	3.52	2.53	–	2.12	1.69	2.82
1994	3.18	2.24	–	1.92	1.45	2.70
1995	3.46	2.37	–	1.69	0.89	2.96
1996	3.66	2.43	1.84	2.76	1.12	3.54
1997	3.91	2.65	2.03	2.53	1.36	3.29
1998	3.05	2.27	1.93	2.08	1.42	2.16
1999	3.14	1.73	1.64	2.27	2.00	2.98
2000	4.72	2.85	2.68	4.23	3.75	4.81

†Source: PH Energy.
‡Source: Natural Gas Week.
Note: cif = cost+insurance+freight (average prices).

6.4.3. *UK natural gas production and consumption*

The British North Sea contains an estimated 26.7 trillion cubic feet (Tcf) of natural gas reserves. Most non-associated gas fields are located off the English coast in the Southern Gas Basin, adjacent to the Dutch North Sea sector. Key producing gas fields include BP Amoco's 5.7-Tcf Leman, Chevron and Conoco's 3-Tcf Brittania, and Shell's 1.7-Tcf Indefatigable and 0.8-Tcf Clipper.

The UK's natural gas industry currently is facing the final stage of liberalisation. The process began in 1986 with the privatisation of the state-held gas monopoly, British Gas. British Gas remained the sole natural gas supplier until 1996, when other companies entered the market. The UK's gas and electricity regulatory body, OFGEM, planned to end all price controls in British gas markets in 2001. A final decision regarding this plan was due to be made in early 2001. The privatisation of the UK's gas industry, leading to an increased gas supply and reduced prices, has helped gas to replace much of the UK's reliance on coal as a source for electricity generation. The natural gas share of utility fuels was 1% in 1988 and is expected to increase to almost 50% by 2010. Privatisation in the UK has progressed well in advance of EU requirements.

In 1998, the UK-Continent Gas Interconnector pipeline was opened, with terminals at Bacton, England and Zeebrugge, Belgium. This is the first natural gas pipeline linking the UK to the European continent. The reversible pipeline was developed by a consortium comprising British Gas (40%), BP (10%), Conoco (10%), Elf (10%), Gazprom (10%), Amerada Hess (5%), Distrigaz (5%), National Power (5%) and Ruhrgaz (5%). The pipeline was intended to allow continental Europe to take advantage of lower UK gas prices. At the end of 1998, British demand peaked

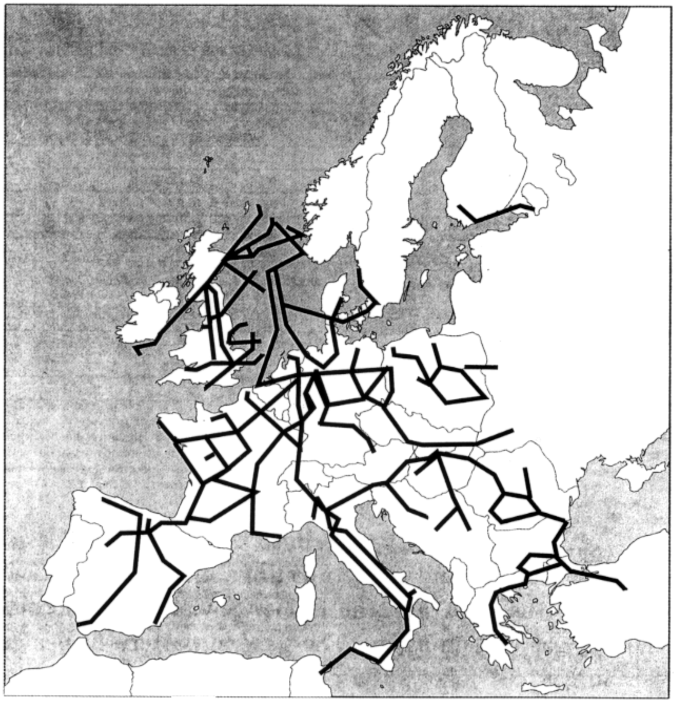


Fig. 6.8. Major European natural gas pipelines [6].

and the pipeline was briefly used to send continental gas supplies to Britain. The Britain–Belgium direction of the pipeline has now been restored. The layout of the major European pipelines is shown in Fig. 6.8 [6].

A new pipeline to connect Ireland to Scottish gas sources in the Corrib field was approved in November 1999, and a plan to connect Ireland to England via Wales was announced in April 2000. A pipeline would run from Manchester, England, underground to Wales, and then under the Irish Sea to just north of Dublin. There is currently one pipeline linking Britain and Ireland, connecting Ireland to Scottish gas sources. Despite these pipeline projects, the UK will remain a much smaller natural gas exporter than North Sea neighbour Norway [5]. A summary of UK production and consumption figures is given in Fig. 6.9. The country changed from being an importer to an exporter of natural gas in 1996 and the proportion of exports is growing. Also, in 1999, 78% of home heating in the UK was fuelled by natural gas [7]. The distribution of UK natural gas consumption between different user sections is shown in Table 6.5. Since 1980 industrial consumption has been relatively stable, growing by 9%, while domestic consumption has grown by 49% and services consumption has more than doubled. However, since 1991 the growth in gas use has been dominated by its increasing use for electricity generation. Electricity generation now accounts for nearly 30% of natural gas consumption in the UK [8].

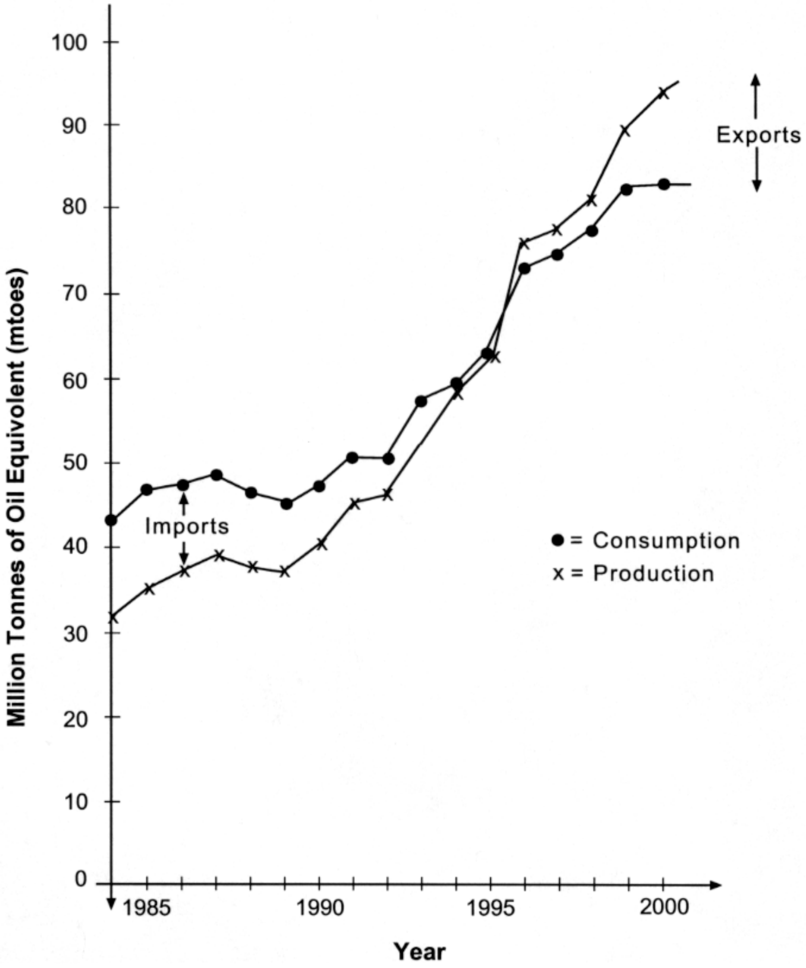


Fig. 6.9. UK natural gas production and consumption.

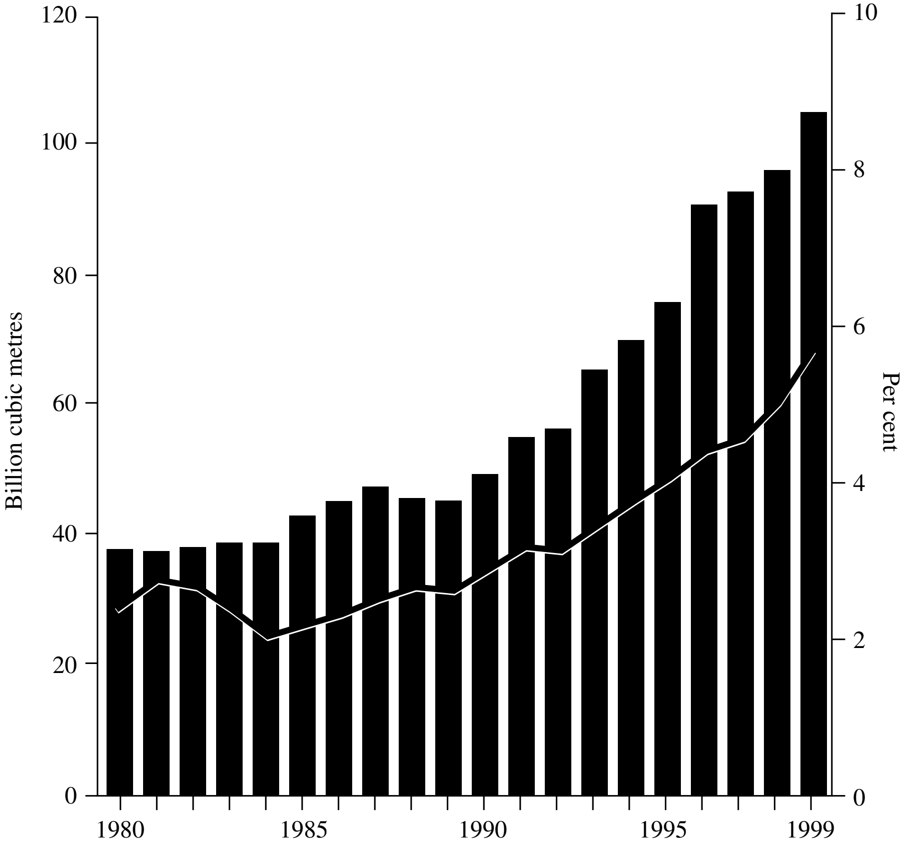
Table 6.5. UK natural gas consumption [8].

TWh

	1970	**1980**	**1990**	**1998**	**1999**	**2000**
Electricity generators	1.8	4.0	6.5	260.7	370.9	312.7
Energy Industries	1.2	19.1	39.2	76.0	76.9	79.7
Industry	20.8	177.5	164.6	194.5	206.0	214.4
Domestic	18.4	246.8	300.4	355.9	358.1	369.9
Services	3.4	60.4	86.4	118.2	119.9	126.8
Total	**45.6**	**507.8**	**597.0**	**1,005.3**	**1,068.8**	**1,103.5**

Another aspect of UK natural gas use is shown in Fig. 6.10 [7]. Gas production, as a proportion of reserves, has nearly trebled in the years since 1985. In 1999, for example, almost 6% of the UK's proven, probable and possible gas reserves were consumed. This should not be taken as an accurate measure of the future life of the gas reserves since additional sources continue to be discovered and developed. It is likely that the production of natural gas will continue at current (2002) levels for longer than is suggested by the present depletion rates [7].

The 1999 prices of natural gas in the domestic sectors of several countries in the European Union and G7 group are shown in the bar chart of Fig. 6.11. Unlike the

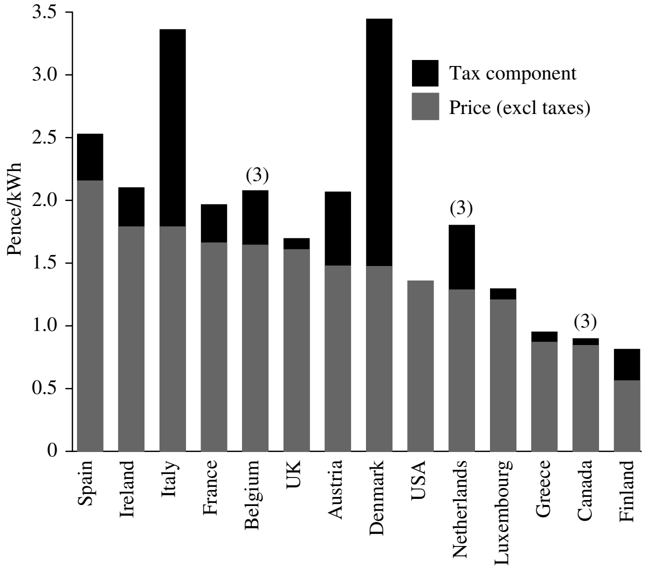


█ Natural gas production (left hand scale)

▬ Annual production as percentage of remaining reserves$^{(1)}$ (right hand scale)

(1) Figures for reserves are the sum of proven, probable and possible reserves remaining. They are the historic estimates of remaining reserves, i.e. the best estimates given at that time.

Fig. 6.10. UK natural gas production [7].



Notes: Tax component represents all taxes levied where not refunded.

(1) Converted using average 1999 exchange rates.

(2) No or only limited gas supply in Sweden and Portugal.

(3) 1998 figures.

Fig. 6.11. Domestic natural gas prices in several EU and G7 countries 1999 (converted to UK pence/kWh) [7].

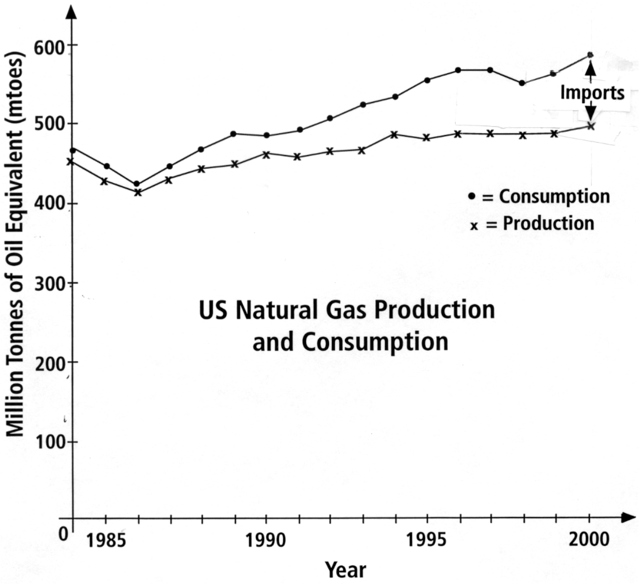


Fig. 6.12.

case with gasoline (Fig. 5.10 of Chapter 5), natural gas is modestly taxed in the UK and carries a purchase price that is about average for the group.

6.4.4. *US natural gas production and consumption*

It is clear from Table 6.3 that the USA is the world's largest user of natural gas, accounting for 27.2% of world consumption in 2000. A summary of the US import/export position is given in Fig. 6.12. The main sites for the importation of natural gas are by pipelines from Canada and Mexico and the oil/gas ports of the Mexican Gulf and of New England, Fig. 6.13 [6].

In terms of per capita consumption the North Americans (principally Canada and the USA) are also the big users, Fig. 6.14, although this has declined since 1970, whereas the per capita consumption in both Western and Eastern Europe increased significantly over the same period. In 2000 the USA and the former Soviet Union accounted for slightly over 50% of the world natural gas consumption. The general pattern of per capita natural gas consumption in Fig. 6.14 follows the pattern for per capita oil consumption in Fig. 5.12 of Chapter 5. World natural gas consumption increased by 19% in the 11-year period from 1990, whereas the US consumption increased by 12% [2].

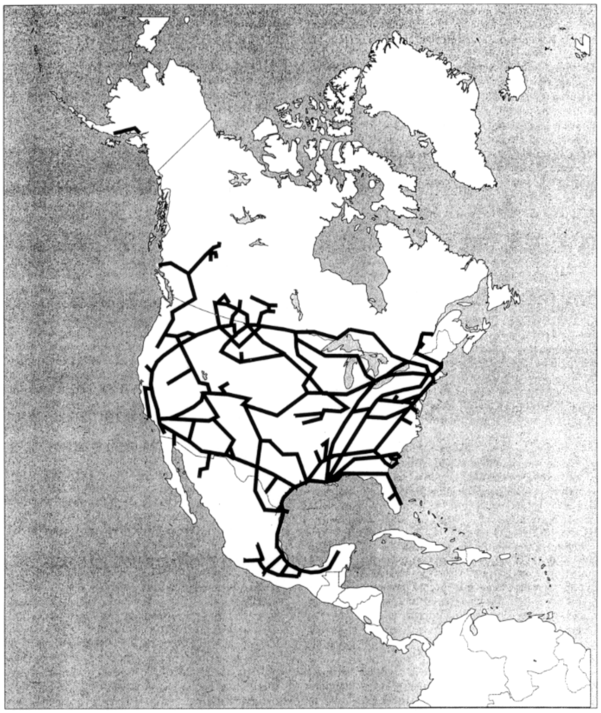
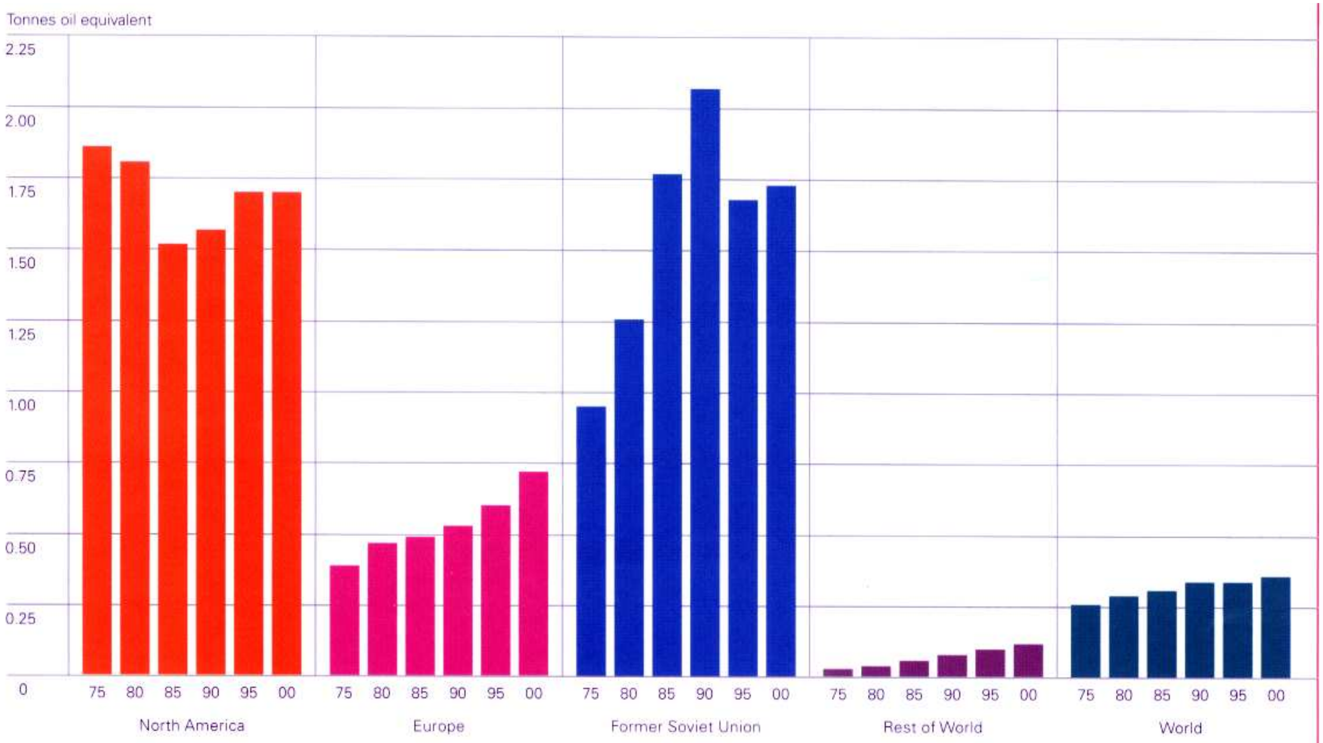


Fig. 6.13. Major North American natural gas pipelines [6].



Consumption per capita continues to grow in Europe and the Rest of World, but remains fairly stable in North America. Three regions (North America, Europe and the Former Soviet Union) are responsible for nearly 75% of the world's natural gas consumption.

Fig. 6.14. Per capita natural gas consumption [2].

It is now accepted that the gas-fired turbine is safe, clean, more efficient than any competing technology, and uncontroversial (in comparison with nuclear power). This has prompted a big switch to gas-fired electricity-generating systems in both Europe and the USA. In the USA it is reported that more than 275 new gas-fired electricity-generating plants are planned to begin by the year 2006. To build a gas-fired electricity generation plant costs about one half the cost of a coal-fired plant of the same rating [9]. Some misgivings are starting to arise as to whether future natural gas supplies will be adequate and will last long enough to justify the present (2002), and now contemplated, scale of financial investment in new plants [10].

The price of natural gas for the US domestic market is among the cheapest of the G7 group of nations, Fig. 6.11 [7]. Significantly, the USA is the only one of the 14 countries quoted that does not tax natural gas.

Several projects are proposed to further increase the import capacity of natural gas from Canada to the USA. The present (2002) estimate is to add 2 billion cubic feet per day of pipeline capacity. Concurrently it is planned to increase exports of natural gas from the USA to Mexico. Although Mexico is rich in natural gas resources, most of this is located in southeastern Mexico, far from the primary consuming areas of the north, and the country lacks the infrastructure to transport the gas [11].

Proven reserves of associated or condensate natural gas increased by 2% in the USA in 1999, to a total of 31,415 billion cubic feet. The areas containing the largest proportions of these reserves correspond to the areas with the largest volumes of crude oil reserves, i.e. Texas (25%), Alaska (23%) and the Gulf of Mexico offshore (21%) [12].

6.5. Coal-Bed Methane

It is known that deposits of coal undergo natural degasification and give off (mainly) methane gas. The methane content increases with depth and with coal rank. In deep coal mines the presence of methane can present a serious health and accident hazard, as discussed in Sec. 4.1.2 of Chapter 4. Safe underground mining procedures require that the methane in deep mines be flushed out with large quantities of air, at considerable expense and considerable waste of valuable natural gas. In 1980 the US Bureau of Mines reported that US mines were venting (and wasting) 256 million cubic feet per day of methane, which was equal to 0.5% of the total dry gas production [12].

6.5.1. *World reserves of coal-bed methane*

Coal-bed methane extraction is now being used to recover useful energy from mining operations and to reduce emissions of methane, whilst also improving safety. One estimate of the total world resource suggests figures of 260×10^{12} m^3, which is 108

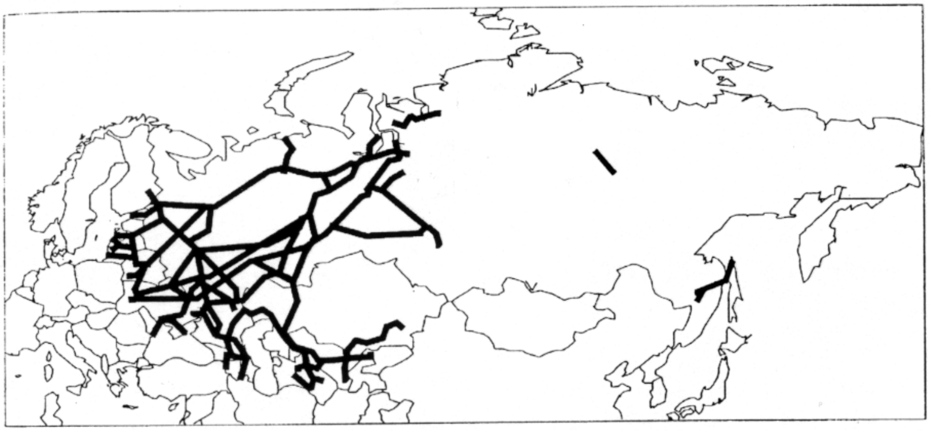


Fig. 6.15. Major Eastern European/former Soviet Union natural gas pipelines [6].

times the world consumption (2404.6×10^9 m^3) of natural gas in 2000. In terms of other fuels the estimate of coal-bed methane reserves is equivalent to about 300,000 Mtonnes of coal or 200,000 Mtonnes of oil. The figure for equivalent oil is greater than the proven world reserves of crude oil (142,100 Mtonnes) in 2000.

The largest known resources of coal-bed methane are in Russia, China, Canada, Australia and the USA (in that order) but there are also significant resources in Germany, Poland, the UK, Ukraine, Kazakhstan, India and southern Africa. Russia also has the advantage of a well-developed infrastructure with extensive pipelines, Fig. 6.15 [6].

In conventional natural gas reservoirs, once the hole is drilled the gas production capacity is generally at a maximum level initially but declines over time. After the well starts to produce, the well pressure begins to decline and gas production decreases with time. With coal-bed methane wells, however, the well may actually increase gas production with time. This is because gas is liberated from the coal by desorption caused by pressure release due to dewatering [13]. The total energy content of the gas obtained by coal-bed methane extraction will not normally exceed 1% of that of the host coal. Coal-bed methane extraction is a way of obtaining useful energy in a readily marketable form but is not equivalent to actually mining the coal. Nevertheless, it provides a means of extracting some energy from coal seams that cannot be mined at all.

6.5.2. *US reserves of coal-bed methane*

A map of the principal US coal basins and estimated "in-place" coal-bed methane resources is given as Fig. 4.7 of Chapter 4.

In 1999, US reserves of coal-bed methane increased 9% to 13,229 billion cubic feet from the 1998 level (12,179 billion cubic feet) to account for 8% of all 1999 dry natural gas reserves. The US Energy Information Administration (EIA) estimated that the 1999 gas reserves of fields identified as having coal-bed methane were more than triple the volume reported in 1989, Fig. 6.16 [12]. Three US states — New Mexico, Colorado and Alabama — are believed to contain 75% of US proven coal-bed methane reserves. It should be noted that the increase of natural gas reserves is due to a combination of new exploration, revised utilisation estimates and improved extraction techniques. Coal-bed methane production grew by about 5% in 1999 to 1252 billion cubic feet, which is about 7% of US dry gas production [14]. It is obvious that coal-bed methane is an important component of the US fuel supply network that is of increasing importance year by year.

Experience in other countries has been less encouraging, generally because their coals have low permeability compared with those in the two main coal-bed methane-producing basins in the USA [13, 15].

The USA and Canada are working jointly to develop the vast, deep, unmineable coal-beds in the Canadian province of Alberta. A process of injecting carbon dioxide is used. When absorbed into the coal this displaces the trapped methane. There is an abundance of deep coal-beds in both countries, providing sites for the geographical storage of carbon dioxide from nearby coal-burning plants and thereby reducing greenhouse gas emissions [16].

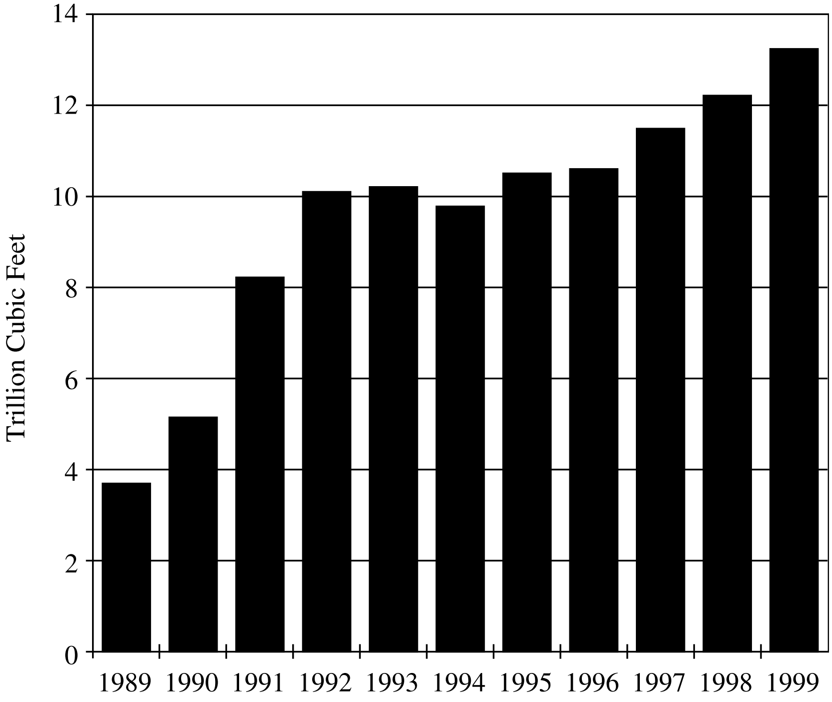


Fig. 6.16. US coal-bed methane proved reserves, 1989–1999 [12].

6.6. Natural Gas Hydrates

A very high potential source of natural gas is from a resource known as "gas hydrates". These have been known about for a number of years but are now considered to be a viable source for extraction of methane gas. This source lies frozen in combustible ice crystals below the ocean floor in the Arctic regions. It has been estimated to represent double the energy potential of all the world's conventional

Table 6.6. World carbon dioxide emissions from natural gas use by region, reference case, 1990–2020.

(Million Metric Tons Carbon Equivalent)

Region/Country	History			Projections				Average Annual Percent Change, 1999-2020
	1990	1998	1999	2005	2010	2015	2020	
Industrialized Countries								
North America	**326**	**377**	**381**	**450**	**499**	**555**	**598**	**2.2**
United States[a]	277	315	317	374	413	460	496	2.2
Canada	35	42	46	49	53	58	63	1.6
Mexico	15	20	19	26	33	37	39	3.4
Western Europe	**140**	**196**	**206**	**259**	**291**	**328**	**385**	**3.0**
United Kingdom	30	47	50	57	65	73	84	2.5
France	16	21	21	29	34	38	46	3.2
Germany	32	42	43	57	62	68	82	3.2
Italy	25	32	35	42	48	54	59	2.5
Netherlands	20	23	22	25	27	28	30	1.4
Other Western Europe	18	31	35	50	56	68	84	4.2
Industrialized Asia	**36**	**52**	**54**	**59**	**62**	**69**	**80**	**1.9**
Japan	24	38	40	43	43	48	56	1.7
Australasia	12	14	14	17	19	21	23	2.3
Total Industrialized	**503**	**626**	**641**	**768**	**852**	**953**	**1,062**	**2.4**
EE/FSU								
Former Soviet Union	369	291	294	317	351	394	440	1.9
Eastern Europe	46	36	35	46	60	78	93	4.7
Total EE/FSU	**414**	**327**	**329**	**363**	**411**	**472**	**532**	**2.3**
Developing Countries								
Developing Asia	**45**	**86**	**92**	**155**	**204**	**263**	**328**	**6.2**
China	8	13	14	31	47	76	108	10.1
India	7	13	12	19	26	36	43	6.1
South Korea	2	8	10	15	19	23	30	5.5
Other Asia	29	53	56	90	111	129	147	4.7
Middle East	**56**	**100**	**102**	**120**	**156**	**187**	**220**	**3.7**
Turkey	2	6	7	7	7	10	13	3.0
Other Middle East	54	94	96	113	148	177	207	3.7
Africa	**22**	**29**	**31**	**36**	**40**	**48**	**54**	**2.7**
Central and South America	**32**	**49**	**51**	**70**	**111**	**173**	**228**	**7.4**
Brazil	2	3	4	8	20	35	48	13.3
Other Central/South America	30	46	47	62	92	138	180	6.6
Total Developing	**155**	**263**	**276**	**380**	**510**	**672**	**831**	**5.4**
Total World	**1,072**	**1,216**	**1,247**	**1,512**	**1,774**	**2,096**	**2,425**	**3.2**
Annex I								
Industrialized	488	606	622	742	819	916	1,023	2.4
EE/FSU	344	296	277	281	284	305	343	1.0
Total Annex I	**832**	**902**	**900**	**1,023**	**1,103**	**1,220**	**1,367**	**2.0**

[a] Includes the 50 States and the District of Columbia. U.S. Territories are included in Australasia.

Notes: EE/FSU = Eastern Europe/Former Soviet Union.

Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 1999*, DOE/EIA-0219(99) (Washington, DC, February 2001). **Projections:** EIA, *Annual Energy Outlook 2002*, DOE/EIA-0383(2002) (Washington, DC, December 2001), Table A19; and World Energy Projection System (2002).

oil, gas and coal reserves combined. No sustained exploration of this source has yet (2002) taken place. It is predicted that serious activity may begin in localised regions, such as the North Slope in Alaska, within the next ten years or so.

6.7. Environmental Aspects of Natural Gas

Natural gas is increasingly viewed as an environmentally friendly fuel. It burns cleaner than coal or oil, causing less local air pollution. The latest figures for carbon dioxide emissions from natural gas use are given in Table 6.6. Comparison with the corresponding Table 5.8 of Chapter 5 for oil shows that gas results in about one half of the oil emission rate at present (2002). The future projections indicate an increasing emission rate over the next decade or so, for all areas of the world, becoming 65% of the oil emission rate by the year 2020.

The countries of Eastern Europe and China, which now rely heavily on coal for electricity generation, increasingly tend to regard natural gas as a more attractive fuel. As one might reasonably expect, there is a direct correlation between the amount of natural gas consumed and the consequent production of carbon dioxide emissions from its use.

An offshore gas platform or any facility handling natural gas is part of the petroleum industry and represents some degree of industrial hazard. The safety record of gas exploration and production, for routine industrial accidents and explosion risks, is excellent in the OECD countries. Nevertheless, gas production, like oil, is required to apply the most stringent safety practices and regulations during exploration and production to guard against leaks, fires and explosions. There has never been a major accident due to gas leakage from transmission pipes or spillage from LNG tankers. Nevertheless, any pipe leaks tend to blanket the surrounding area with gas, thus excluding oxygen, and can leave an area barren for months.

The combustion of natural gas causes the oxidation of atmospheric nitrogen. Nitrogen oxides are formed which contribute to acid precipitation. In association with sulphur dioxide the nitrogen oxides can be toxic to plant life. The total effects of natural gas use are, however, much less severe than those of coal.

6.8. Synthetic Gas from Coal

Until the widespread use of natural gas in the 1950s and 1960s the term “gas” meant “coal gas” or “town gas” in most countries of the world. It has long been known that coal undergoes low temperature natural degasification, described in Sec. 6.5 on coal-bed methane.

Coal gas was used as a fuel for street lighting in several European countries before the end of the 18th century. The 19th century saw the widespread development of the coal gas industry right across the world. In the USA high temperature coal gasification was a commercial industry for 150 years, ending in the mid-1950s [17].

By the end of the 19th century the amount of coal used in coal gas production in Britain was just over 13 million tonnes, which was more than for the rest of Europe together [18].

In Britain, the old-style "gas works" with its characteristic malodorous stench, piles of coal for processing and storage gasometer tanks had largely disappeared by the early 1960s. It is an interesting irony that world stocks of coal will long outlast the reserves of oil and natural gas. The use of coal as a base material to once again manufacture coal gas (and also possibly oil) is a possible future scenario for the early part of the 21st century.

The UK policy of drastic curtailment of the once great coal mining industry, in favour of natural gas and imported coal, may turn out to be short-sighted. Senior geologists in the UK have commented that it will not be possible/practicable to reopen the old deep coal mines. Things would have to start up again by drilling new shafts and boring new tunnels if the need again arises to increase the production of domestic deep coal. On the other hand, the use of imported coal preserves the indigenous coal, which can be used as a source of coal-bed methane.

All modern high temperature coal gasification processes follow similar stages to produce either low BTU, medium BTU or high BTU coal gases. Coal or coke is crushed and heated in the presence of air or oxygen. Several different industrial methods, such as the Lurgi process, have been developed in Europe. These differ only with regard to the method of bringing the reactants into contact with the coal. Gas made from passing air or an air-steam mixture over hot coal is called *low BTU* gas and has the low calorific value of 3–6 MJ/m^3. This gas, which consists mainly of nitrogen plus the combustible components carbon monoxide and hydrogen, cannot be economically transported or used in equipment designed for natural gas. It can be used to power on-site industrial boilers. A useful application is for economic electric power generation using combined-cycle plants, as described in Chapter 4.

If oxygen is used, rather than air, the reaction produces a gas called *medium BTU* gas, which has a calorific value of 10–22 MJ/m^3. Most of the diluting nitrogen is removed by this process, leaving mainly carbon monoxide. If methane or other hydrocarbons are added to increase the upper-end calorific properties, this fuel acquires a heating value about one half that of natural gas. It burns rapidly and can produce a flame temperature higher than that of natural gas. The high carbon monoxide content prevents it from being distributed in the natural gas pipeline network [1].

High BTU gas is thermally equivalent to natural gas, having a calorific value of 37 MJ/m^3 or 1000 BTU/ft^3. It is interchangeable with natural gas and can be transmitted in the natural gas pipeline network. This synthetic natural gas (SNG) is produced by the methanation of medium BTU gas. A number of investigations are currently proceeding to develop more effective and economic methods of producing SNG. The aim is to produce high methane gas and reduce the need for oxygen in the gasifier. In the UK there is an industrial catalytic process for producing natural gas (methane) from oil.

It is possible to produce coal gas directly from a coal seam by underground gasification. A controlled fire is started underground, fed by oxygen, air or steam, producing low BTU gas in the combustion area. This technique has some environmental appeal and was tried extensively in the former USSR during the 1930s [18]. In the UK the underground gasification process would be in direct competition with the most profitable coal mines and is not presently economical [19]–[21].

6.9. Problems and Review Questions

6.1. Use the data of Tables 6.2 and 6.3 to list, in order, the world's current ten largest producers and consumers of natural gas.

6.2. Why did the consumption of natural gas in Eastern Europe start to fall so significantly after about 1990?

6.3. In which countries of the world did the annual consumption of natural gas increase most rapidly during the 1990s?

6.4. What are the world's busiest trade routes for natural gas?

6.5. Is the UK self-sufficient in the use of natural gas? Explain using figures of UK production and consumption of natural gas from 1984 to the present time.

6.6. Is the USA self-sufficient in the use of natural gas? Explain using figures of US production and consumption from 1984 to the present.

6.7. The consumption of natural gas has slowly risen in the UK since 1990. What has been the average annual increase?

6.8. The consumption of natural gas has slowly risen in the USA since 1989. What has been the average annual increase?

6.9. What proportion of the world consumption of natural gas was used by the western OECD countries in the year 2000?

6.10. What proportion of the world natural gas reserves is currently located in (a) North America, (b) Europe, (c) former Soviet Union, (d) Middle East, (e) Africa, (f) Asia and Australia?

6.11. Why has the world stock of natural gas "proved reserves" increased since 1980 in spite of a continuous rise of consumption in the same period?

6.12. If the Middle Eastern countries become the chief exporters of natural gas by the middle of the present century, how will this gas probably be transported to Western Europe?

6.13. What is the probable chief source of synthetic natural gas?

6.14. Draw up a table of low BTU, medium BTU and high BTU gases in terms of their calorific values.

6.15. Why is natural gas projected to become increasingly popular as a prime fuel source, compared with coal, for electricity generation?

6.16. Explain the differences between natural gas, coal-bed methane and coal gas.

6.17. Why has the enormous potential of coal-bed methane, as a viable fuel source, only recently received serious attention?

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CHAPTER 7

GEOTHERMAL ENERGY

7.1. Introduction

Geothermal energy is thermal energy stored in the sub-surface of the earth. It is not a renewable source because prolonged exploitation can exhaust a particular site. Nevertheless, the vast extent of energy potentially available is such that many references refer to it as if it was infinitely renewable. Energy is stored in natural underground reservoirs of steam and/or hot water, known as aquifers, and also in "hot sediments" that are buried at depth or adjacent to hot spots.

Heat energy flows outwards from within the earth at the average rate of 0.063 W/m^2. The total outward flow amounts to 32×10^{12} W, as shown in Fig. 2.1 of Chapter 2. It is of interest that the amount of interior heat flux flowing outwards is only about one-thousandth the value of the solar energy flux falling from space onto the same area [1, 2]. The surface geothermal heat distribution is too small and too diffuse to be exploited except in concentrated hot spots such as geysers or volcanoes.

7.2. Geological Structure of the Earth

The geological structure of the earth is illustrated in Fig. 7.1 [3]. It is believed to approximate to five concentric spheres. From the outside proceeding inwards these are the atmosphere, crust, mantle, liquid outer core (magma) and solid inner core. As one proceeds inwards the temperature and density increase. For non-volcanic (i.e. non-seismic) areas the average geothermal gradient is between 17°C and 30°C per kilometre of depth (50°–87°F per mile). In volcanic areas the temperature gradient is much higher.

The earth's crust, composed of basalt, silicate rocks, is not of uniform thickness. Under the oceans the crust is about 15 km thick and consists of porous rock. Under the continental land masses the crust is about 35 km thick, Fig. 7.2, and the proportion of porous rock probably increases with depth. Between the continental

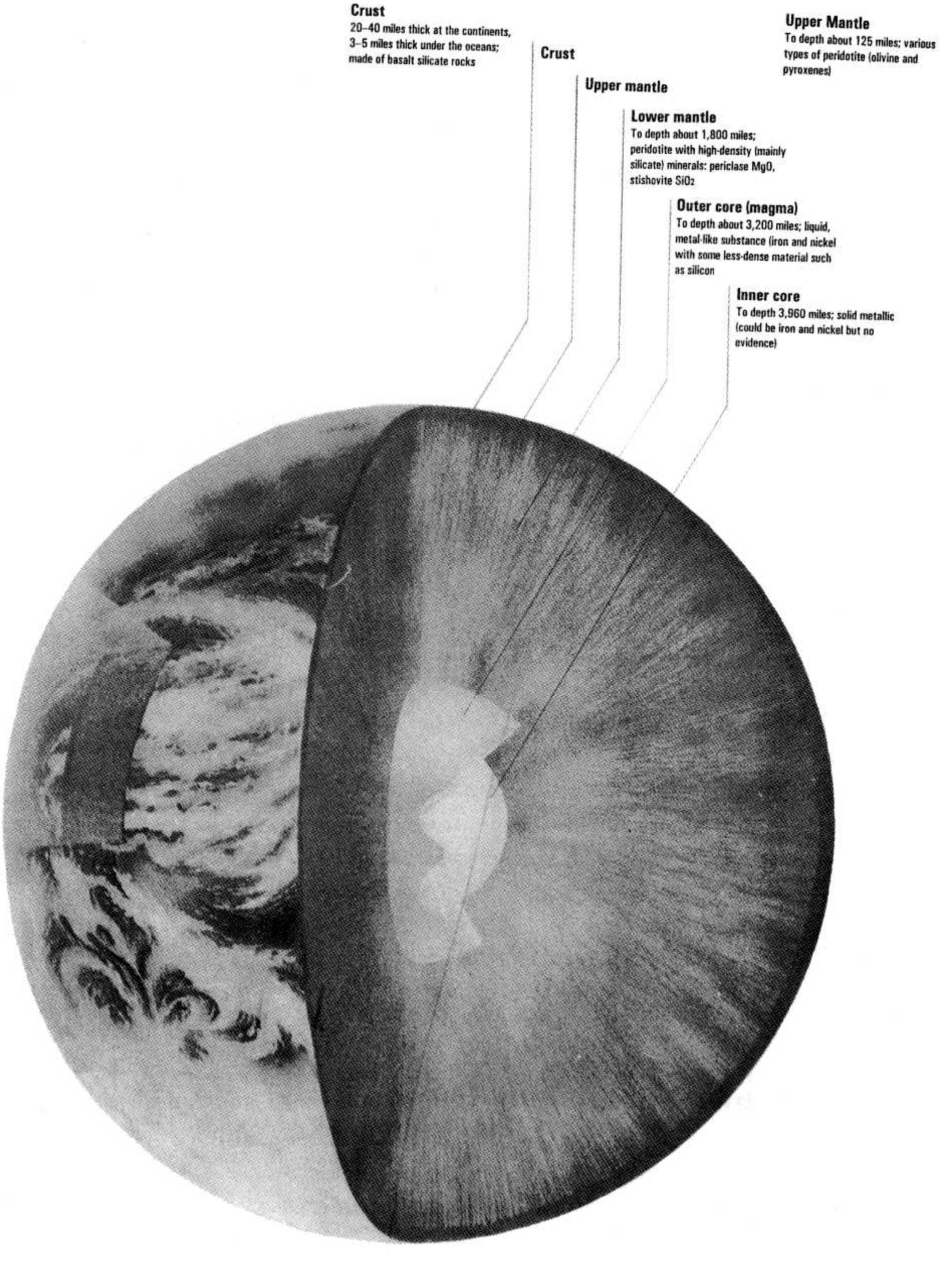

Crust
20–40 miles thick at the continents,
3–5 miles thick under the oceans;
made of basalt silicate rocks
Crust
Upper mantle
Upper Mantle
To depth about 125 miles; various
types of peridotite (olivine and
pyroxenes)
Lower mantle
To depth about 1,800 miles;
peridotite with high-density (mainly
silicate) minerals: periclase MgO,
stishovite SiO2
Outer core (magma)
To depth about 3,200 miles; liquid,
metal-like substance (iron and nickel
with some less-dense material such
as silicon
Inner core
To depth 3,960 miles; solid metallic
(could be iron and nickel but no
evidence)

Fig. 7.1. Structure of the earth [3].

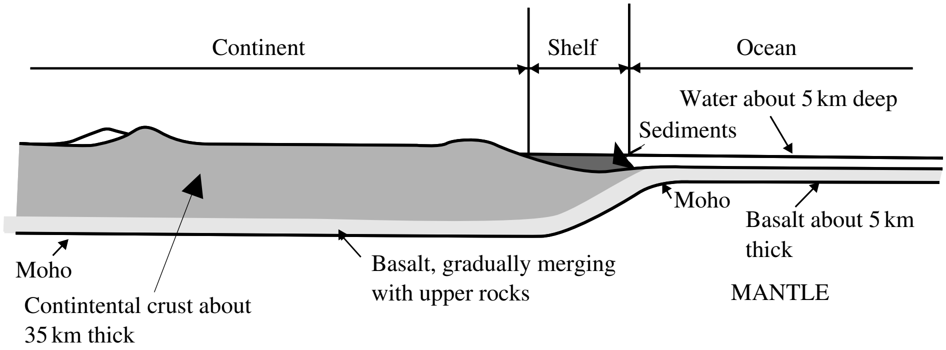


Fig. 7.2. Schematic section through the earth's crust [4].

land mass and the ocean, the continental shelf contains a great thickness of sedimentary rocks such as sandstone or limestone [4]. Most offshore oil and natural gas exploration occurs in the continental shelf areas.

The crust is not a solid annular shell but consists of several massive rigid segments, known as tectonic plates. These plates can move relative to each other (sometimes called "continental drift"). Plate tectonic theory suggests that pressure builds up at the plate boundaries and sudden movements at the plate interfaces result in earthquakes. It is difficult to control large-scale geological effects. Some serious work is under way in California, USA, using water injection to lubricate and reduce the friction on the plate edges. Usually, seismic disturbance cannot be accurately predicted.

The crust is composed of many diverse elements, and there is much variation in the chemical composition of the rocks from geographical region to region. The younger marginal platforms adjacent to a continent consist mainly of the sedimentary rocks derived from continued erosion of the continental surface. The platforms often form beds up to several miles in thickness. The oldest known rocks of the Precambrian shields generally consist of igneous rocks such as granite and highly metamorphosed gneiss (i.e. laminated) rocks.

Between the crust and the earth's mantle is a boundary called the Mohorovicic seismic discontinuity. In Fig. 7.2 this is identified as the "Moho". This boundary layer represents some form of material and physical state different from the crust rock composition.

Below the Moho is the mantle, which forms the major part of the earth (80% by volume). It is made of highly viscous, partially molten rock with temperatures between 650°C and 1250°C and is thought to be largely composed of mixtures of magnesium and iron silicates. The upper and lower mantles, Fig. 7.1, are about 590 miles and 1180 miles thick respectively. Volcanic "ejecta" is composed of silicates from the mantle.

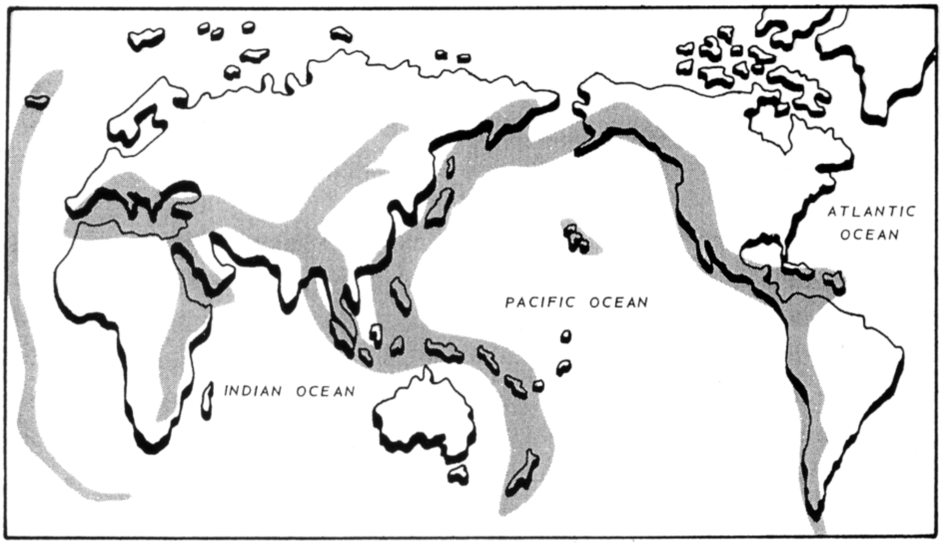


Fig. 7.3. Regions of intense geothermal activity [5].

There have been many speculations about the nature of the materials which make up the inner core and outer core ("magma"). Most of the studies have pointed towards a liquid/solid metal core made up of iron or iron nickel, but these can only be inspired scientific guesses. The outer core is about 1310 miles thick, while the inner core has a radius of about 840 miles [3]. In the core temperatures may reach 4000–7000°C (7200–12,600°F).

There is no present technology capable of directly controlling or even approximating the enormous heat store of the core material. Cracks or fissures occur in the earth's crust, sometimes in regions where there is an underlying intrusion of magma into the crust due to tectonic plate motion. Plumes of magma ascend by buoyancy and force themselves up into the crust, bringing up vast quantities of heat [5]. In these locations volcanoes are formed. The volcanic action is impressive and formidable, sometimes awesome and beautiful, but it is not predictable or controllable. Volcanoes still remain a hazard rather than an energy opportunity. Figure 7.3 shows the earth's regions of high geothermal activity [6]. The British Isles and Ireland do not appear on this map but are known to be non-seismic.

7.3. Origin of Geothermal Heat Flow

The classical explanation of geothermal heat flow is that heat energy is being conducted from the very hot interior regions of the earth to its surface. Through the epochs of time the outer crust formed as a result of faster cooling rate. Masses of molten rock circulating within the magma by gravitational action cause friction forces that generate heat [7]. A more modern theory postulates that the earth is a giant furnace. Radioactive decay of potassium, uranium and thorium in the earth's crust generates heat. Additional heat is generated by smaller concentrations of radioactive materials within the mantle below the crust [2]. The correct explanation may never be known but might incorporate both of the present theories.

7.4. Geothermal Energy Resources

The amount of geothermal energy within the earth is enormous. It is important to note, however, that no reliable numerical estimate of its value is available, either from individual national sources or from international sources. Many estimates have been made, with widely different results. An assessment by the World Energy Conference in 1980 for the geothermal resource base of the continental land masses to a depth of 3 km, for electricity generation purposes, at a modest extraction fraction, gave a value of 36×10^{20} J [8]. This was about ten times the total world primary energy consumption at that time. All numerical estimates of the geothermal energy resources should be regarded as speculative. What is undeniable, however, is that there is a vast amount of energy, most of which is presently untapped. At a depth of 6 miles, the approximate average temperature of the earth is greater than 100°C. Interestingly, however, there are many "hot spots" on the earth which are much shallower. The total stored geothermal energy exceeds by several orders of magnitude the total fossil and nuclear resources. Only solar energy is comparable in total magnitude [6].

7.5. Geothermal Reservoirs

Water heated by the hot magma rock can rise to the surface as hot liquid springs or steam. One of the best-known of these is the Geysers of Northern California, USA. Natural mineral waters have been used throughout the world for their therapeutic and medicinal values for at least 2000 years. Mineral baths dating from the Roman era (55 BC – 400 AD) may still be visited in Bath, England. Health spas using geothermally heated water have flourished in Europe, Asia, the Middle East, North and South America, South-East Asia and New Zealand. The map of Fig. 7.3 shows that geothermal energy is far more widely distributed than oil or natural gas. For instance, it might prove to be a valuable energy resource for the poor countries of East Africa.

Groundwater and snowmelt sink through the permeable rocks of the crust, such as sandstone or limestone, or penetrate through fissures into porous rock deposits. Such deposits may be several miles deep. In the porous areas the water is heated by the underlying magma and circulates by convection, sometimes circulating all the way back to the surface as water or steam, Fig. 7.4.

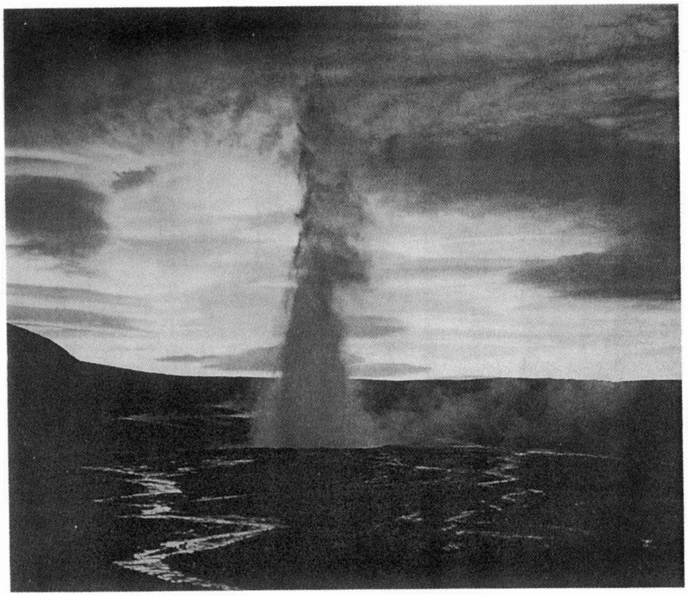
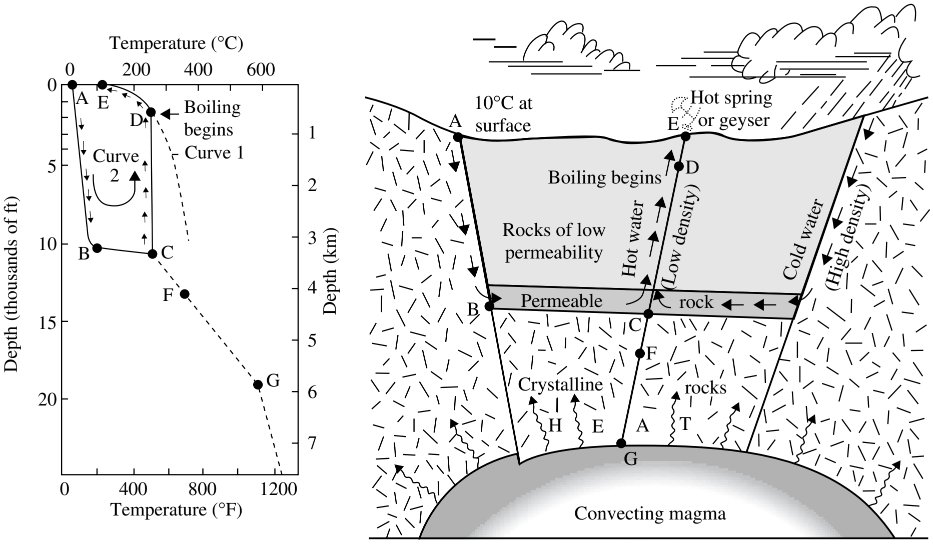


Fig. 7.4. A geyser on the mid-Atlantic ridge at Strokkur, Iceland.


Temperature (°C)
0
200
400
600
0
5
10
15
20
Depth (thousands of ft)
1
2
3
4
5
6
7
Depth (km)
A
E
D
Boiling
begins
Curve 1
Curve
2
B
C
F
G
0
400
800
1200
Temperature (°F)
10°C at
surface
A
Hot spring
or geyser
E
D
Boiling begins
Rocks of low
permeability
Hot water
(Low density)
Cold water
(High density)
Permeable
rock
B
C
F
Crystalline
rocks
H
E
A
T
G
Convecting magma

(a) (b)

Fig. 7.5. Geological illustration of hot-water geyser action.

(a) Reference curve for the boiling point of pure water.

(b) Temperature profile along a typical circulation route (from *Characteristics of Geothermal Sources*, by D. E. White in Ref. 6).

At surface (atmospheric) pressure water will boil at a temperature of 100°C (212°F). Because of the high pressures within the earth at a depth of 5–6 miles, the water remains liquid and does not boil and change to steam, even at temperatures of several hundred degrees centigrade. Its density is gradually reduced due to volumetric expansion causing it to rise to the surface by buoyancy. Sometimes the pressure conditions are such that the rising water changes to steam (with consequent reduction of pressure) as it rises and emerges from the ground through natural vents or man-made bore holes, as steam geysers or fumaroles, Fig. 7.5 [6, 7].

If the ascending hot water meets an impermeable rock layer, the water is trapped underground where it fills the pores and cracks, comprising 2–5% of the volume of the surrounding rock, forming a geothermal reservoir [5]. Geothermal reservoirs can be tapped down to depths of about 8000 ft. Even at 500°C the high pressure may prevent the reservoir water from boiling. Water or steam temperatures as high as 700°C may occur. The drilling rigs are the same land-based mobile units used in the oil and gas industries.

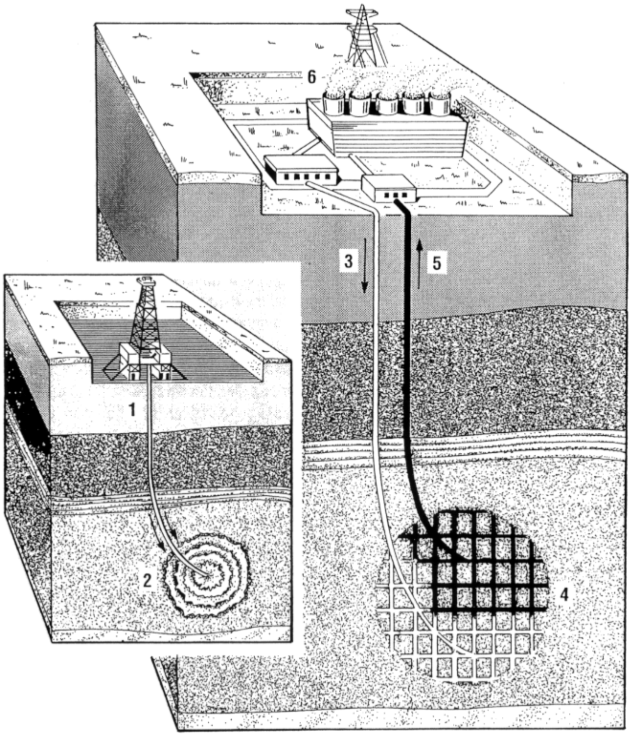
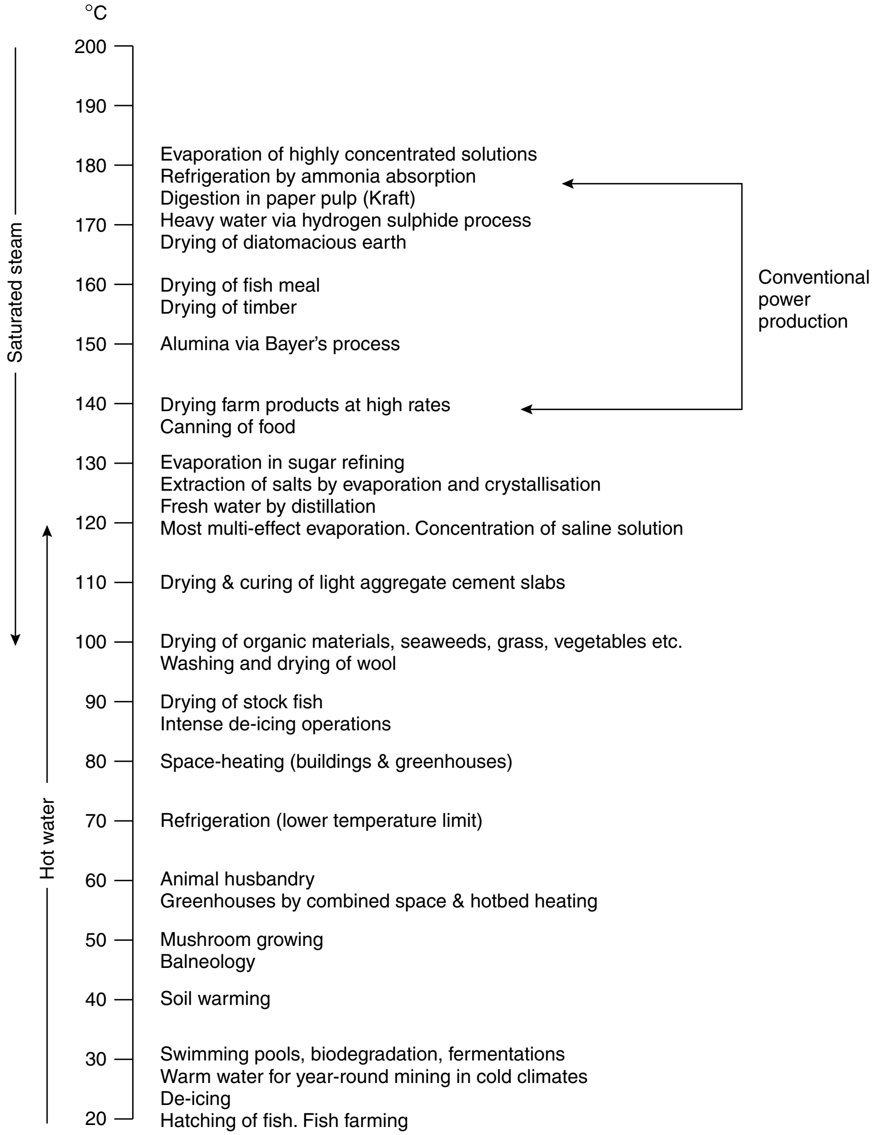


Fig. 7.6. Hot rock method of tapping geothermal energy source [14].
1. Drilling two holes for injected water.
2. Explosive fracturing.
3–5. Injected cold water returns hot.
6. Geothermal power plant.

Large sedimentary basins may contain reservoirs at much smaller depths where the water is thermally heated in the range 100–200°C. These may have surface outlets in the form of hot springs or boiling mud pools [8].

Hot water up to temperature of 75°C can be obtained from low-grade, semi-thermal aquifers by drilling to depths of 1.5–2 km. This corresponds to a temperature gradient of 30°C/km. Such low-grade sources can be found in non-thermal (i.e. non-seismic) areas, including southern England, but are only worth exploiting for space heating if they are near to large centres of population, Fig. 7.6 [2, 8]. In

Table 7.1. Approximate temperature requirements (°C) of geothermal fluids for various applications [4].



Saturated steam
Hot water
Conventional power production

°C	
200	
190	
180	Evaporation of highly concentrated solutions Refrigeration by ammonia absorption Digestion in paper pulp (Kraft)
170	Heavy water via hydrogen sulphide process Drying of diatomacious earth
160	Drying of fish meal Drying of timber
150	Alumina via Bayer's process
140	Drying farm products at high rates Canning of food
130	Evaporation in sugar refining Extraction of salts by evaporation and crystallisation
120	Fresh water by distillation Most multi-effect evaporation. Concentration of saline solution
110	Drying & curing of light aggregate cement slabs
100	Drying of organic materials, seaweeds, grass, vegetables etc. Washing and drying of wool
90	Drying of stock fish Intense de-icing operations
80	Space-heating (buildings & greenhouses)
70	Refrigeration (lower temperature limit)
60	Animal husbandry Greenhouses by combined space & hotbed heating
50	Mushroom growing Balneology
40	Soil warming
30	Swimming pools, biodegradation, fermentations Warm water for year-round mining in cold climates
20	De-icing Hatching of fish. Fish farming

Marshwood, Dorset, England, projects have been run where cold water was injected into hot, porous sediment and recovered as hot water.

Some of the many industrial applications for which geothermally heated water or steam has been used are given in Table 7.1 [4, 10]. Heat of almost any grade available from geothermal fluids (liquids or gases) can be used. It is useful to remember that about 90% of the world energy consumption is used for heating purposes [11].

The problem of geothermal application is one of availability rather than applicability. If geothermal energy was widely available it could contribute 20–50% of the energy needs of an industrialised country. But in the countries of northern Europe and the eastern parts of the Americas it is not an available source.

7.6. Locations and Types of Principal Geothermal Sources

There are four main types of geothermal sources: dry steam, wet steam, hot brine and hot rock. Hyperthermal fields, both wet and dry, are confined to the seismic areas shown in Fig. 7.3. In some locations the presence of the geothermal energy is evident through surface ports such as geysers. Good sources have also been detected in locations devoid of visible manifestations.

7.6.1. *Dry steam sources*

Dry geothermal fields produce dry saturated steam or superheated steam at pressures of several atmospheres. These usually occur at the deepest drilling ranges. This type of deposit is the rarest but is the easiest and most economical to tap because there is little corrosion problem. The best-known example is the Geysers development near San Francisco, California, USA.

7.6.2. *Wet steam sources*

Wet geothermal fields produce pressurised water at temperatures in the range 180–370°C, which often contains impurities/contaminants such as sulphur compounds/gases. When the fluid is brought to the surface, about 10–20% of it flashes into steam due to pressure reduction. Wet steam fields appear to be about 20 times more abundant than dry steam fields. There are no known steam sources, wet or dry, in the UK and no recorded geyser activity. In Iceland, however, homes are commonly heated from geothermal sources. Also, geothermal heat is used there in greenhouses to grow tropical fruit such as bananas.

7.6.3. *Hot brine sources*

Abundant geothermal energy is known to exist worldwide within hot brine (i.e. salt-solution) deposits. A particularly large source of low-temperature geothermal energy is the geopressurised brines of the sedimentary basins of the Mexican Gulf coast in the USA and Mexico. These brines may also hold very large amounts of dissolved natural gas at temperatures below 180°C. If the heat and the gas could be exploited simultaneously this would be an attractive resource [12].

The volume of brine that would need to be handled would be enormous. Where brine deposits lie under the land then the removal of massive volumes of liquid could create major ecological dislocation, such as land subsidence. Some form of liquid re-injection might be needed, as shown in Fig. 7.6. The high salinity of the brines is very corrosive to the equipment used to handle it and represents another good ecological reason for re-injection.

Some geothermal aquifers can be largely pollution-free and gaseous emissions are small. Other aquifers are offensive and environmentally unfriendly in their local impact.

7.6.4. *Dry rock sources*

Most of the potentially exploitable geothermal heat is stored in dry rocks, rather than in water or steam aquifers. The normal geothermal temperature gradient, worldwide, is 20–30°C/km, as stated in Sec. 7.2 above. This is sufficient to produce temperatures of 80°C for space heating at depths of 2.2 km and temperatures of up to 180°C at the accessible depth of 5.5 km. In locations of a semithermal and hyperthermal geological nature, where the geothermal gradient is higher, sometimes much higher, than 40°C/km, the subterranean hot rock is called “hot dry rock”.

Various types of steam and hot water aquifers or reservoirs are relatively easy to tap because the storage medium of the energy is also the heat transfer fluid. In order to exploit the heat energy of hot rock, however, it will be necessary to fracture the rock, to inject water as a working fluid and also to develop a network of channels through which water can flow in and out, Fig. 7.6. Fracturing of the rock can be achieved by inducing thermal stresses using cold water or by chemical or nuclear explosions. This technique is similar in principle to that proposed for shale oil extraction, in Sec. 5.5.1 of Chapter 5.

Although a number of prototype investigations of hot rock exploitation have been reported, there are no commercial plants. Too little is yet known about the feasibility of exploiting pressurised brines or hot dry rocks to judge the ecological consequences [12].

The characteristics of the four main types of geothermal sources are summarised in Table 7.2 [11].

7.6.5. *Molten magma*

Magma, or molten lava, is the extreme case of hot rock. It has been found, at temperatures higher than 650°C, in pools at the surface of volcanoes or in reservoirs below them. There are no practical means of extracting the heat, although some research is in progress.

Table 7.2. Characteristics of four types of geothermal sources [11].

Type/Characteristic	*Dry steam*	*Wet steam*	*Hot brine*	*Hot rock*
Ease of utilisation	Highest (greatest ease)	Somewhat difficult	Difficult	Greatest difficulty
Abundance	Lowest	Somewhat abundant	Abundant	Great abundance
Drilling depth	8000 ft (2440 m)	3000 ft (915 m)	4500 ft (1370 m)	10,000 ft (3050 m)
Pressure and temperature of steam or water	7 atmospheres, 200°C	2 atmospheres, 230°C	1 atmosphere, 240°C	400°C
Fields operating in 1978	Larderello, ltaly; Geysers, USA; Matsukawa, Japan	Wairakei, New Zealand; Cerro Prieto, Mexico	None	None
Exploration sites		Kilauea Volcano, Hawaii	Imperial Valley, Calif.	Marysville, Montana; Vallez Caldera, New Mexico

7.7. Worldwide Applications of Uses of Geothermal Energy

The biggest use of geothermal energy is in the generation of electricity, which is discussed in Sec. 7.12 below. In addition there is widespread use of geothermal heat energy for direct (non-electrical) applications. Geothermal direct use applications provide about 10,000 thermal megawatts of power in about 35 countries. A summary of some country-by-country use is given in Table 7.3, representing the 1998 situation [5]. A more extended consideration of the detailed uses and main users of geothermal energy follows.

7.8. Geothermal Prospects in the UK

7.8.1. *Shallow drilling*

The UK does not possess geothermal sources in the form of aquifers, which contain water hot enough to provide steam for electricity generation [13]. Water with a maximum temperature of about 90°C is available and can be used for district heating or local industrial applications. With aquifer water hotter than 60°C the surface yield can be used directly in district heating schemes without the use of heat pumps.

A major geothermal project for commercial heating was undertaken in Southampton, England, in the early 1980s. At a drilling depth of 1675 m the water temperature was 74°C. The flow rate of test extracted water showed that the geothermal reservoir was unexpectedly small, such that the source lifetime would be

Table 7.3. Direct (non-electrical) use of geothermal power [5].

Country/Area	Power ($MW_{thermal}$)
European Union	
Austria	21.1
France	309
Germany	307
Italy	314
UK	2
Non-EEC — European	
Georgia	245
Iceland	1443
Hungary	750
Russia	210
Switzerland	190
Turkey	160
TOTAL EUROPEAN	4645
North America	
Canada	3
USA	1905
Asia	
China	1914
TOTAL ASIAN	3075
TOTAL WORLD	9704

10–20 years. Because a lifetime of 25 years was the minimum needed for economic viability, the original project was scaled down in 1984 [14]. It remains in operation, however, as the only commercial use of geothermal energy in the UK. Council offices and private sector buildings are linked by a 2 km hot water main running to and from a "heat station" close to the well-head [9].

The British Geological Survey has drilled a number of 300 m bore-holes in various parts of the UK to measure local heat flows. Potential aquifers were identified in the Wessex Basin, East Yorkshire and Lincolnshire, the Worcester Basin, West Lancashire and Cheshire, and also in Northern Ireland. Regrettably, however, the temperatures or potential yields are too low for exploitation.

The present (2002) cost of aquifer resource heat is about two-and-a-half times that from conventional commercial sources. Other difficulties are the cost of drilling "dry" wells, drilling component failures and variations of surface housing density [9].

Several areas of the UK have impermeable granite rock formations close (i.e. within a few hundred feet) to the surface, which are likely to be large heat stores. Some investigation has been made of using explosive charges to fracture granite at the bottom of 2 km bore-holes. It is estimated that it would be necessary to bore down to 6 km in Cornwall, UK, to reach rock at a temperature of 180°C, which would be suitable for electricity generation. This is not, at present, an economic proposition.

An enticing longer term prospect is the possible exploitation of deep basement rocks as hot rock sources. Where these lie close to the centres of population, with their high density heat loads, the possibility arises of both district heating and electricity generation. Little is still known about the deep geology of the UK. If the deep rocks are impermeable and if suitable drilling techniques can be developed, then hot rock geothermal energy could become available on a large scale.

The potential for geothermal energy in the UK is the equivalent of ten years of electric power. But the technological problems of extracting heat from underground aquifers and hot dry rocks are very difficult and the economics are unattractive [15].

7.8.2. *Worked example*

A geothermal aquifer supplies hot water with a well-head temperature of 75°C at the flow rate of 20 litres/s. The heat energy is used to supplement a district heating unit above a datum temperature of 40°C. If the geothermal heat is used for 170 days each year, how much oil is saved annually if the overall combustion efficiency of the oil burner is 75%? (Based on a problem in Ref. 2.)

Flow rate $= 20$ litres/s
$= 20 \times 3600$ litres/hour
$= 20 \times 3600 \times 24$ litres/day
$= 20 \times 3600 \times 24 \times 170$
$= 294 \times 10^6$ 1litres/working year

Volume of water transferred per working year (1 litre $\equiv 1000\ \text{cm}^3$) $= 294 \times 10^6 \times 10^3 \times \text{cm}^3$

Mass of water transferred per working year ($1\ \text{cm}^3 \equiv 1$ gm) $= 294 \times 10^6 \times 10^3$ g
$= 294 \times 10^6$ kg

Temperature contribution above the datum $= 75 - 40 = 35$°C

Heat transferred per working year $= 294 \times 10^6 \times 10^3 \times 35$
$= 10.29 \times 10^{12}$ cals

Now 1000 tonnes of oil (Ref. 3 of Chapter 5) $\equiv 10 \times 10^{12}$ cals

Oil saved per year at 100% efficiency $\equiv 10.29/10 = 1029$ tonnes

Oil saved per year at 75% efficiency $\equiv 1029/0.75 = 1372$ tonnes

7.9. Geothermal Uses in the USA and Elsewhere

The greatest application of US geothermal energy is in the production of electricity, which is discussed in Sec. 7.12. In addition there are many direct (non-electrical) uses of geothermally heated water, described in the following subsections.

7.9.1. *Hot springs and bathing spas (balneology)* [5]

For centuries the peoples of China, Iceland, Japan, New Zealand, North America and other areas have used hot springs for cooking and bathing. The Romans used geothermal water to treat eye and skin disease and, at Pompeii, to heat buildings. Medieval wars were even fought over lands with hot springs. Today, as long ago, people still bathe in geothermal waters.

In Europe, natural hot springs have been very popular health attractions. The first known "health spa" was established in 1936 in Belgium. (One resort was named "Espa", which means "fountain". The English word "spa" came from this name.) All over Eurasia today, health spas are still very popular. Russia, for example, has 3500 spas.

Japan is considered the world's leader in balneology. The Japanese tradition of social bathing dates back to ancient Buddhist rituals. Beppu, Japan, has 4000 hot springs and bathing facilities that attract 12 million tourists a year. Other countries with major spas and hot springs include New Zealand, Mexico and the USA. The USA has 218 spas that use geothermally heated water.

7.9.2. *Agriculture*

Geothermal resources are used worldwide to boost agricultural production. Water from geothermal reservoirs is used to warm greenhouses to help grow flowers, vegetables and other crops. For hundreds of years, Tuscany in central Italy has produced vegetables in the winter from fields heated by natural steam. In Hungary, thermal waters provide 80% of the energy demand of vegetable farmers, making Hungary the world's geothermal greenhouse leader. Dozens of geothermal greenhouses can also be found in Iceland. In the western United States there are now (2002) 38 geothermally heated greenhouse complexes.

7.9.3. *Aquaculture*

Geothermal aquaculture, the "farming" of water-dwelling creatures, uses natural warm water to speed the growth of fish, shellfish, reptiles and amphibians. This kind of direct use is increasing in popularity. In China, for example, geothermal aquaculture is growing so fast that fish farms cover almost 2 million square metres (500 acres). In Japan, aqua farmers grow eels and alligators. In the USA 28 geothermal aqua farmers in Idaho, Utah, Oregon and California grow catfish, trout, alligators and tilapia — as well as tropical fish for pet shops.

7.9.4. *Industry*

The heat from geothermal water is used worldwide for industrial purposes. Some of these purposes are drying fish, fruits, vegetables and timber products, washing wool, dyeing cloth, manufacturing paper and pasteurising milk. Geothermally heated water can be piped under pavements and roads to keep them from icing over in freezing weather. Thermal waters are also used to help extract gold and silver from ore and even for refrigeration and ice-making.

7.10. Geothermal District Heating [5]

The oldest and most common use of geothermal water, apart from hot spring bathing, is to heat individual buildings, and sometimes entire commercial and residential districts. A geothermal district heating system typically supplies heat by pumping geothermal water — usually 60°C (140°F) or hotter — from one or more wells drilled into a geothermal reservoir. The geothermal water is passed through a heat exchanger which transfers the heat to water in separate pipes that is pumped to the buildings. After passing though the heat exchanger, the geothermal water is injected back into the reservoir, where it can reheat and be used again.

In the Paris basin in France, historic records show that geothermal water from shallow wells was used to heat buildings over six centuries ago. An increasing number of residential districts there are being heated with geothermal water as the drilling of new wells progresses. The first district heating system in the USA dates back to 1893 and still serves part of Boise, Idaho. In the western United States there are over 270 communities that are close enough to geothermal reservoirs for potential implementation of geothermal district heating. Eighteen such systems are already in use in the USA — the most extensive being in Boise, Idaho and San Bernardino, California.

Because it is a clean, economical method of heating buildings, geothermal district heating is becoming more popular in many places. Besides France and the USA modern district heating systems now warm homes in Iceland, Turkey, Poland and Hungary. The world's largest geothermal district heating system is in Reykjavik, Iceland, where almost all of the buildings use geothermal heat. The air around Reykjavik was once very polluted by emissions from reliance on fossil fuels. Since it started using geothermal energy, Reykjavik has become one of the cleanest cities in the world.

7.11. Geothermal Heat Pumps [5]

In many parts of the world the earth temperature is stable in the range 45–58°F a few feet below the surface. Animals burrow into the earth to escape the excessive winter and/or summer air temperatures. Indoor temperatures can be kept comfortable using the earth's heat by means of a geothermal heat exchange system known as a geothermal heat pump (GHP). A GHP will circulate water or other liquids through pipes buried in a continuous loop, horizontally or vertically, adjacent to a building. The system can be used for either heating or cooling.

Heating

The difference between the earth's temperature and the colder temperature of the air is transferred through the buried pipes into the circulating liquid and hence into the building.

Cooling

During hot weather the continuously circulating fluid in the pipes absorbs heat from the building and transfers it into the earth.

A GHP system uses only a small electric pump motor — probably much less than 1 kW rating — and is environmentally friendly.

In the USA there are now (2002) estimated to be about 300,000 homes, schools and offices incorporating geothermal heat pump systems. The US Environmental Protection Agency has rated GHPs as among the most efficient of heating and cooling technologies.

7.12. Electricity Generation from Geothermal Sources

Hot water and/or steam available from geothermal sources can generate electricity via the use of steam turbines. No fossil fuel is burned. The first commercial system used steam to provide electric lighting in Larderello, Italy [16]. Until 1958 Italy was the only country where natural steam was used for electrical power generation on an industrial scale [2]. This was followed by electrical power production in New Zealand and the USA. There are major developments by Union Oil in northern California, USA, to produce geothermal energy. The largest geothermal power plant in the world is at the Geysers, near San Francisco, USA.

7.12.1. *Worldwide geothermal electrical power production* [5]

As of 1999, 8217 megawatts of electricity were being produced from some 250 geothermal power plants running day and night in 22 countries around the world. These plants provide reliable base-load power for well over 60 million people, mostly in developing countries. The generation figures for some countries are shown in Table 7.4.

The world's leading producer of geothermal electric power is the USA. About 2850 MW of geothermal generation capacity is available from power plants in the western United States. Geothermal energy generates about 2% of the electricity in Utah, 6% of the electricity in California and almost 10% of the electricity in northern Nevada. The electrical energy generated in the USA from geothermal resources is more than twice that from solar and wind combined.

Table 7.4. Geothermal electrical power production, l999 [5].

Producer Country	Power ($\mathrm{MW_e}$)
United States	2850
Philippines	1848
Italy	768.5
Mexico	743
Indonesia	589.5
Japan	530
New Zealand	345
Costa Rica	120
Iceland	140
El Salvador	105
Nicaragua	70
Kenya	45
China	32
Turkey	21
Russia	11
Portugal (Azores)	11
Guatemala	5
France (Guadeloupe)	4
Taiwan	3
Thailand	0.3
Zambia	0.2
Total	8217 $\mathrm{MW_e}$

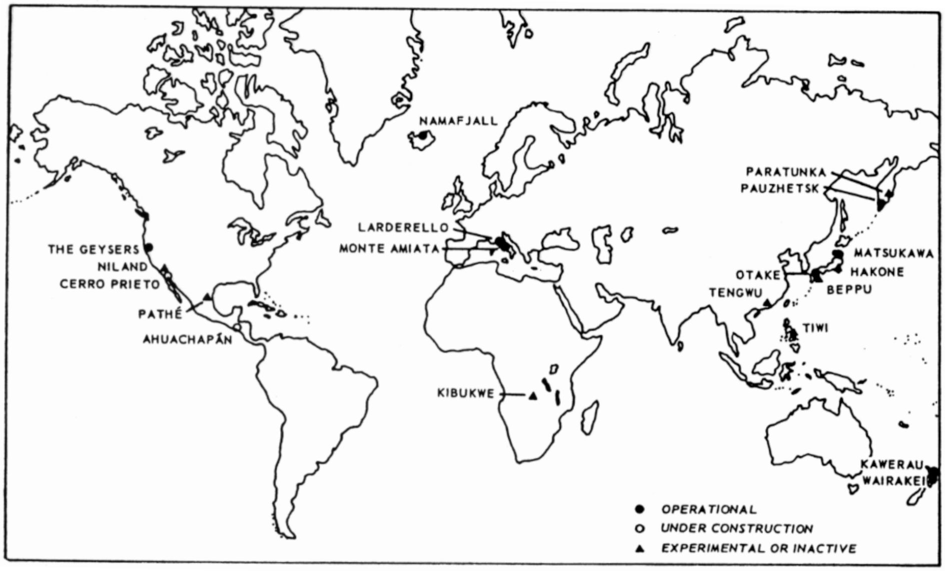

NAMAFJALL
PARATUNKA
PAUZHETSK
LARDERELLO
MONTE AMIATA
THE GEYSERS
NILAND
CERRO PRIETO
PATHÉ
AHUACHAPÁN
MATSUKAWA
OTAKE
HAKONE
TENGWU
BEPPU
TIWI
KIBUKWE
KAWERAU
WAIRAKEI
● OPERATIONAL
○ UNDER CONSTRUCTION
▲ EXPERIMENTAL OR INACTIVE

Fig. 7.7. Geothermal electricity power stations (from "Worldwide Status of Geothermal Resources Development", by J. B. Koening, in Ref. 6).

7.12.2. *Technologies of geothermal electrical power generation* [5]

(A) *Flash steam plants.* Most geothermal power plants operating today are "flash steam" power plants. Hot water from production wells is passed through one or two separators where, released from the pressure of the deep reservoir, part of it flashes (explosively boils) to steam. The force of the steam is used to spin the turbine generator. To conserve the water and maintain reservoir pressure, the geothermal water and condensed steam are directed down an injection well back into the periphery of the reservoir, to be reheated and recycled.

(B) *Dry steam plants.* A few geothermal reservoirs produce mostly steam and very little water. Here, the steam shoots directly through a rock-catcher and into the turbine. The first geothermal power plant was a dry steam plant, built at Larderello in Tuscany, Italy in 1904. The power plants at the Larderello dry steam field were destroyed during World War II, but have since been rebuilt and expanded. That field is still producing electricity today. The Geysers dry steam reservoir in northern California has been producing electricity since 1960. After 40 years it still produces enough electricity to supply a city the size of San Francisco.

(C) *Binary power plants.* In a binary power plant, the geothermal water is passed through one side of a heat exchanger, where the heat is transferred to a second (binary) liquid, called a working fluid, in an adjacent separate pipe loop. The working fluid boils to vapour, which, like steam, powers the turbine generator. It is then condensed back to a liquid and used over and over again. The geothermal water passes only through the heat exchanger and is immediately recycled back into the reservoir.

Although binary power plants are generally more expensive to build than steam-driven plants, they have several advantages: (1) the working fluid (usually isobutene or isopentane) boils and flashes to a vapour at a lower temperature than does water, so it is possible to generate electricity from reservoirs with lower temperatures; this increases the number of geothermal reservoirs in the world with electricity-generating potential; (2) the binary system uses the reservoir water more efficiently; since the hot water travels through an entirely closed system it results in less heat loss and almost no water loss; (3) binary power plants have virtually no emissions.

(D) *Hybrid power plants.* In some power plants, flash and binary processes are combined. An example of such a hybrid system is in Hawaii, where a plant provides about 25% of the electricity used on the Big Island.

7.12.3. *Locations of geothermal electricity-generating stations*

Some locations of present and intended geothermal generation sites are shown in Fig. 7.7. Comparison with Fig. 7.3 shows that these all lie in tectonic regions.

Geothermal energy remains one of the real energy prospects for developing countries. In 1976 exploration programmes had been set in motion in 35 countries [4]. By 1989 the installed capacity mix for electrical generation in Mexico included 32% from hydroelectricity and 3% from geothermal. In Mexico geothermal power has been developed to the point where the Comision Federal de Electricidad (Mexico's state-owned electricity utility) sells 70 $\mathrm{MW_e}$ of geothermally generated electricity to a utility in southern California, USA [17].

In Europe the only viable sites for geothermally generated electricity are likely to remain Iceland and Italy. There is no prospect of geothermal electricity generation in the UK.

A listing of the geothermally produced electric power in several countries is given in Table 7.4.

In the USA, for example, California generates 824 $\mathrm{MW_e}$ at the Geysers plant, 490 $\mathrm{MW_e}$ at the Imperial Valley, 260 $\mathrm{MW_e}$ at Coso and 59 $\mathrm{MW_e}$ at smaller plants. Although the Geyser operates much below its capacity, it is still the world's largest developed geothermal field and an outstandingly successful renewable energy project.

7.13. Environmental Features of Geothermal Power

A number of possible environmental problems may arise in the development and use of geothermal energy sources.

7.13.1. *Geothermal site exploration and development*

The initial exploitation of a site, especially drilling operations, is likely to cause noise, surface damage and local disruption. Access roads may need to be installed or improved to facilitate the transportation of building materials and heavy machinery. The development site will contain drilling rigs, exhaust vents, and building of various kinds, machinery and pipework. Depending on location, some of this may be of objectionable visual impact.

Any geothermal development has to be associated with a heat distribution system. As with electricity, oil and gas distribution, customers want the energy but not the means of delivering it. The necessary pipelines need to pass over or under existing land and to terminate in industrial structures.

A geothermal plant sits right on top of its fuel source: no additional land is needed, such as for mining coal or for transporting oil or gas. When geothermal power plants and drill rigs are located in scenic areas, mitigation measures are implemented to reduce intrusion on the visual landscape. Some geothermal power plants use special air-cooling technology which eliminates even the plumes of water vapour from cooling towers and reduces a plant profile to as little as 24 ft in height [5].

7.13.2. *Protection of the local atmosphere*

Hydrogen sulphide gas (H_2S) sometimes occurs in geothermal reservoirs. H_2S has a distinctive rotten egg smell that can be detected by the most sensitive sensors (our noses) at very low concentrations (a few parts per billion). It is subject to regulatory controls for worker safety because it can be toxic at high concentrations. Equipment for scrubbing H_2S from geothermal steam removes 99% of this gas [5].

Early attempts at geothermal drilling in the UK were accompanied by clouds of waste steam and a strong smell of hydrogen sulphide [4]. These adverse effects can be largely contained and some geothermal aquifer sites are largely pollution-free. Gaseous emissions are then usually negligible and there are no noticeable fumes. The problem of local air pollution is always present at geothermal sites. It is claimed that air pollution standards at the Geysers field have resulted in cleaner air than before the field was exploited [2, 4].

Carbon dioxide (a major climate change gas) occurs naturally in geothermal steam but geothermal plants release amounts less than 4% of that released by fossil fuel plants. There are no emissions at all when closed-cycle (binary) technology is used [5].

7.13.3. *Protection of ground water* [5]

Geothermal water contains a higher concentration of dissolved minerals than water from cold groundwater aquifers. In geothermal wells, pipe or casing (usually several layers) is cemented into the ground to prevent the mixing of geothermal water with other groundwater.

When highly mineralised geothermal water needs to be stored at the surface, such as during well testing, it is kept in lined, impermeable sumps. After use, the geothermal water is either evaporated or injected back in its deep reservoir, again through sealed piping.

7.13.4. *Enhancement of reservoir water*

A unique example of enhancing reservoir water is at the Geysers steam field in California, where treated wastewater from nearby communities is being piped to a steamfield and injected into the reservoir to be heated. This increases the amount of steam available to produce electricity. With this enhancement, reservoir life is increased while providing nearby cities with an environmentally safe method of wastewater disposal.

7.13.5. *Ecological effects of geothermal plants*

Ecological effects are specific to location. The release of some gaseous toxic emissions could destroy animal habitats and affect local flora and fauna. The US

Environmental Protection Agency has conducted tests, in the vicinity of geothermal development sites, on animal tissues and animal products, as biological monitors. Concentrations of geothermal effluents in animal tissue were examined, mainly in rodents because of their importance in the food chain for snakes, hawks, owls, coyotes, foxes, etc. The samples were analysed for selected elements to confirm ongoing baseline tissue concentrations [18].

7.13.6. *Effects on local geological structure*

Present geothermal sites use existing technologies for natural sources of steam and hot water. These do not present any geological hazard. Future geothermal exploration is likely to involve either hot dry rocks or geopressurised brines, both of which imply possible geological dislocation.

The fracturing of rocks at depth, by explosion, to provide access for large volumes of water could contaminate groundwater, cause surface subsidence or trigger seismic disturbances. If large-scale exploitation of the normal earth thermal gradient eventually becomes feasible, then either natural or induced seismic disturbances might be very serious [4, 12].

As noted in Sec. 7.6.3, the exploitation of geopressurised brine would involve the displacement of enormous volumes of fluid. This highly saline and polluted liquid could not be dumped into rivers or onto land surfaces after it has passed through the heat exchangers. There are few applications where the contaminated water could be passed straight into tidal estuaries. The most feasible solution would seem to be re-injection into the ground but the specific geological result of this is not known.

7.14. Problems and Review Questions

7.1. What are the present theories to explain why temperature increases with depth of penetration into the earth?

7.2. Why does water in geothermal aquifers remain in the liquid state even though its temperature may be much higher than 100°C?

7.3. In what parts of the world would you expect to see surface evidence of geothermal energy, such as steam geysers or volcanoes?

7.4. Identify on a map the volcanoes Cotopaxi, Fijivama, Hekla, Katmai, Kileauea, Krakatoa, Lassenpeak, Mauna Loa, Mount Etna, Mount St Helens, Ngouruhoe, Osorno, Paricutin, Popocatepeti, Semeru, Stromboli. Comment on the overall result [14].

7.5. Why is Iceland Europe's largest grower of bananas?

7.6. Identify the countries associated with the geothermal field sites listed in Table 7.4. Do these countries all lie in the tectonic (seismic) areas shown in Fig. 7.3?

7.7. Why is the UK unlikely to be able to use geothermal aquifer energy on any significant scale?

7.8. What are the principal forms of geothermal energy resource?

7.9. What are the disadvantages to the use of hot dry rocks as a major heat source?

7.10. Explain, using a diagram, the basis of the process of extracting heat from subterranean hot dry rocks.

7.11. What are the environmental features associated with geothermal energy exploration and development?

7.12. Why was the proposed UK geothermal scheme at Southampton curtailed from it originally estimated level of activity?

7.13. What are the main world locations for geothermally generated electricity? Why is the UK not a viable site?

7.14. A geothermal district heating scheme issues a flow rate of 22.5 litres/s with a well-head temperature of 70°C. It supplies heat above a datum temperature of 40°C for a period of 162 days/year. If the overall combustion efficiency of the oil burner is 73%, how much oil is saved per year?

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CHAPTER 8

NUCLEAR ENERGY

8.1. Basic Atomic Theory

All matter is believed to be composed of small particles, called atoms. These are the smallest particles of any chemical element possessing the chemical properties of that element. Most of the materials and substances that abound in nature or are manufactured have basic constituents, called molecules, that are compounds of different atoms.

The atom itself is not the smallest particle in nature but is believed to be comprised of various sub-atomic particles. Most of the mass of an atom is concentrated in its nucleus, which is composed of positively charged protons and zero-charged neutrons, collectively referred to as nucleons. The nucleus is surrounded by much lighter, negatively charged particles called electrons which are in continuous motion in three-dimensional orbits.

In any atom there are equal numbers of protons and electrons, resulting in zero overall charge, and this number is called the "atomic number". The atomic number also represents the location of the atom in the Periodic Table of Chemical Elements and so characterises its chemical properties. For example, the element hydrogen is the lightest element with an atomic number of unity while the heaviest naturally occurring element is uranium with an atomic number of 92.

Protons and neutrons have (very nearly) equal mass but do not normally combine in equal numbers. The total number of these nucleons in an atomic nucleus is referred to as the atomic mass number in atomic mass units (amu). Each amu has the value 1.66×10^{-27} kg. It is possible for the atomic nucleus of a chemical element to have several versions, whereby the same number of protons may be combined with different numbers of neutrons. When this situation arises, the different versions of the element are called isotopes. For example, normal hydrogen has a nucleus consisting of one proton with the atomic mass number 1. But there is also a naturally occurring stable isotope of hydrogen called deuterium (D) that has a nucleus containing one proton plus one neutron so that its atomic mass number is 2.

Uranium has three isotopes with the same atomic number of 92 but mass numbers of 234, 235 and 238. These isotopes are usually designated U234, U235 and U238, respectively. The actual mass of a hydrogen atom, consisting of one proton plus one electron, is 1.007825 amu, while the actual mass of a neutron is 1.00867 amu.

Chemical reactions usually involve combination of the atoms of different elements to form molecules — basic building blocks — of a further different compound substance. Sometimes chemical reactions take the form of interactions between the orbiting electrons of adjacent atoms. Some examples of this are given in Chapter 12 and refer to certain semiconductor materials used in photovoltaic cells for solar energy applications. In chemical reactions the nuclei of the atoms involved remain intact.

8.2. Basic Nuclear Theory

8.2.1. *Nuclear fission*

Nuclear reactions are not the same as chemical reactions. They involve fragmentation by splitting of the nuclei of atoms for the purpose of releasing some of the considerable binding energy. Mass is a form of energy and Einstein expressed the equivalence of mass m and energy W in the form

$$W = mc^2 \tag{8.1}$$

where m is in kilogrammes, W is in joules and c is the velocity of electromagnetic wave (light) propagation, (very nearly) 3×10^8 m/s. For example, the energy equivalent of 1 atomic mass unit is

$$\begin{aligned} W &= 1.66 \times 10^{-27} \times (3 \times 10^8)^2 \text{ J} \\ &= 14.94 \times 10^{-11} \text{ J} \\ &\equiv 4.147 \times 10^{-17} \text{ kWh} \\ &\equiv 931 \text{ MeV} \end{aligned} \tag{8.2}$$

Under appropriate physical conditions the nuclei of some heavy atoms can be fragmented if they are bombarded with neutrons — a process known as nuclear fission. Some of the consequent released energy appears in the form of heat. The best-known and most-used example of nuclear fission, discovered in 1938 by two German scientists, Otto Hahn and Fritz Strassman, is illustrated in Fig. 8.1 [1]. When the nucleus of a U235 atom absorbs an extra neutron, it divides into two fragments of roughly equal mass, generating a large amount of heat and releasing either two or three more neutrons plus some gamma radiation. The two fission fragments are respectively nuclei of the elements barium and krypton. This process, shown artistically in Fig. 8.1, can be expressed in the nuclear equation

$${}^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{92}\text{Kr} + {}^{141}\text{Ba} + 3\text{n} + \gamma \tag{8.3}$$

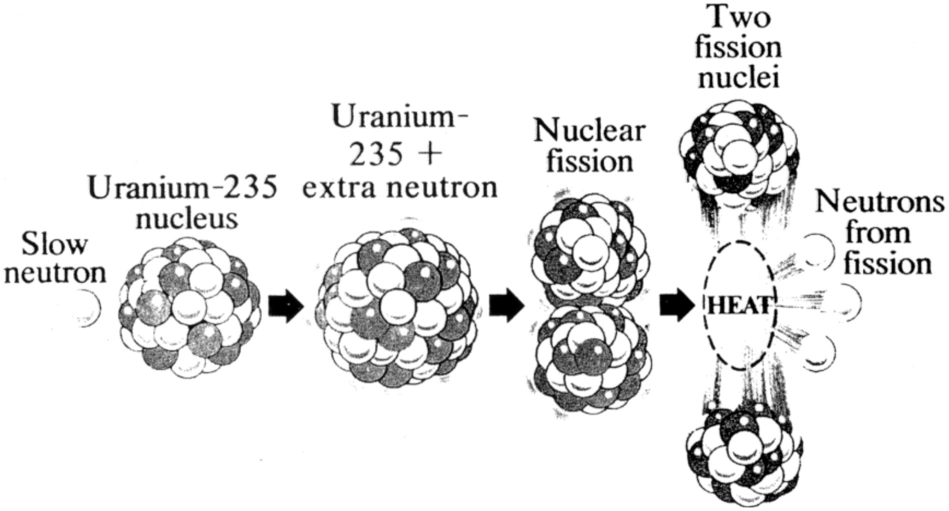


Fig. 8.1. Uranium fission [1] (reproduced by permission of AEA Technology plc).

where n = neutron and γ = gamma radiation. The atomic mass numbers of the fission fragments sum to $92 + 141 = 233$, which is smaller than the mass number 235 of the uranium. Now the atomic mass units add to 236 on both sides of (8.3). But each fission is known to release energy equivalent to a loss of mass (called the mass defect) of 0.215 amu or $(0.215)\ (1.66 \times 10^{-27})$, which is 3.57×10^{-28} kg. By Einstein's equation (8.1) each uranium atom fission therefore has the energy equivalent of

$$\begin{aligned} W &= 3.57 \times 10^{-28} \times (3 \times 10^{8})^{2} \\ &= 3.2 \times 10^{-11} \text{ joules/fission} \\ &= 200 \text{ MeV} \end{aligned} \tag{8.4}$$

One kilogramme of U235 contains 2.5×10^{24} atoms. If this is completely fissioned the energy released would be

$$\begin{aligned} W_{\text{from 1 kg of U235}} &= 3.2 \times 10^{-11} \times 2.5 \times 10^{24} \\ &= 8 \times 10^{13} \text{ J} \end{aligned} \tag{8.5}$$

In comparison, the thermal energy content of a ton of coal is about 3×10^{10} J. One kilogramme of fissioned U235 is therefore roughly equivalent, in thermal energy terms, to $(8 \times 10^{13})/(3 \times 10^{10}) = 2700$ tons of coal. It is also roughly energy equivalent to about 2000 tonnes of oil.

8.2.2. *Worked examples*

Example 8.1

One kilogramme of U235 contains 2.5×10^{24} atoms. What mass of U235 has the energy equivalence of 1 ton of coal?

$$\begin{aligned}
&\text{Thermal energy content of 1 ton of coal} \approx 3 \times 10^{10}\ \text{J}\\
&\text{The fission of 1 atom of U235 releases} \quad \equiv 3.2 \times 10^{11}\ \text{J}\\
&\text{The fission of 1 kg of U235} \qquad\qquad\quad \equiv 3.2 \times 10^{-11} \times 2.5 \times 10^{24}\\
&\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\ \equiv 8 \times 10^{13}\ \text{J}
\end{aligned}$$

Therefore, in energy terms,

$$\begin{aligned}
1\ \text{kg U235} &\equiv \frac{8 \times 10^{13}}{3 \times 10^{10}}\\
&\equiv 2670\ \text{tons of coal}
\end{aligned}$$

Example 8.2

Naturally occurring uranium contains 0.7% of fissionable U235 and 99.3% of largely non-fissionable U238. Assume that, in a particular fission process, only 1% of the U235 was fissioned. What mass of uranium ore is then the thermal energy equivalent of 1000 tons of coal?

When pure U235 is completely fissioned, then, from Example 8.1,

$$1000\ \text{tons of coal} \equiv 0.375\ \text{kg},\ \ \text{U235}$$

If only 1% of the U235 is fissioned, then

$$\begin{aligned}
1000\ \text{tons of coal} &= 100 \times 0.375\\
&\equiv 37.5\ \text{kg},\ \ \text{U235}
\end{aligned}$$

If U235 is contained within the uranium ore in the proportion 0.7% (without any enrichment), then

$$\begin{aligned}
1000\ \text{tons of coal} &\equiv 37.5 \times \frac{100}{0.7}\\
&\equiv 5357\ \text{kg},\ \ \text{U235}\\
&\equiv \frac{5357}{2.205} = 2429\ \text{lb}\\
&\equiv \frac{2429}{2240} = 1.08\ \text{tons of ore}
\end{aligned}$$

8.3. Radioactivity

8.3.1. *Nature of radioactivity*

Some of the heavier chemical elements have isotopes that are intrinsically unstable. Their nuclei undergo spontaneous degeneration in order to achieve a more stable energy form. Such materials are known as radioactive and the process of degeneration is known as radioactive decay. Examples of naturally occurring radioactive substances are radium, thorium and uranium. The decay chain of an element involves natural transmutation into a chemically different element and a succession of such changes may occur.

For a radioactive source, the following features may be of interest:

(a) energy (intensity) level
(b) time-scale of decay
(c) nature of the radiation
(d) effects of the radiation

8.3.2. *Energy and decay rate*

The energy radiated from a radioactive source and the time rate of decay are both proportional to the number of radioactive atoms contained in it.

Let a source contain N radioactive atoms at an arbitrary instant t. The time rate of decay is then

$$\frac{dN}{dt} = -\lambda N = \text{decay rate} = \text{activity} \tag{8.6}$$

The negative sign in (8.6) indicates that the number of atoms disintegrating decreases with time in the manner shown in Fig. 8.2. The unit of activity is called the curie (Ci), which represents 3.7×10^{10} atomic disintegrations/second. It therefore defines the quantity of a specific radioactive source of known decay rate. One curie is equal to the activity of about 1 g of radium. The term λ in (8.6), called the decay constant, is a characteristic of the radioactive material and is entirely independent of the physical conditions. A mathematical expression for the activity or decay rate is obtained by integrating both sides of (8.6):

$$\int_{N_0}^{N} \frac{dN}{N} = -\int_0^t \lambda \, dt \tag{8.7}$$

If there are initially N_0 atoms present, at $t = 0$, then at an arbitrary time t thereafter

$$\lambda t = -\ln\left(\frac{N}{N_0}\right) = \ln\left(\frac{N_0}{N}\right) \tag{8.8}$$

Taking anti-logs of both sides of (8.8) gives

$$N = N_0 \in^{-\lambda t} \tag{8.9}$$

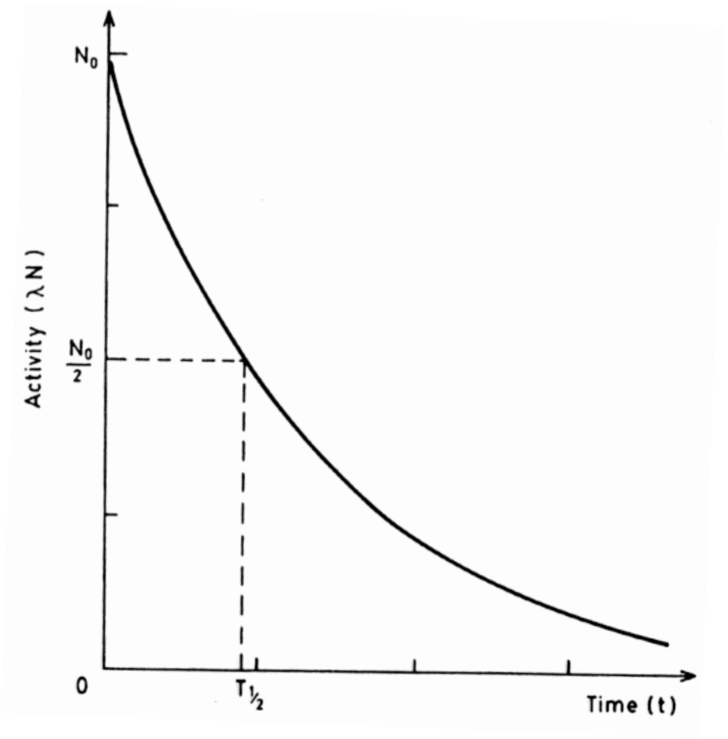


Fig. 8.2. Nature of radioactive decay.

A material with an exponential rate of decay does not reduce to zero until infinite time has passed. Equation (8.9) is zero only when $t = \infty$. In order to distinguish decay rates for different materials, it is customary to define a decay rate in terms of its "half-life", i.e. the time for one-half of the radioactivity to decay.

In (8.8), when $N = N_0/2$, the half-life $T_{1/2}$ is given by

$$\lambda t = \lambda T_{\frac{1}{2}} = \ln(2) = 0.693 \tag{8.10}$$

or

$$T_{\frac{1}{2}} = \frac{0.693}{\lambda}$$

Half-lives vary from fractions of a second to millions of years, depending on the radioactive material.

8.3.3. *Worked examples*

Example 8.3

How long does it take a radioactive source to decay to one-tenth of its original size? What is the value for U235 which has a half-life of 7.1×10^8 years?

From (8.8)

$$t = \ln \frac{\left(\frac{N_0}{N}\right)}{\lambda}$$

Eliminating λ between (8.8) and (8.10) gives

$$t = \frac{\ln \frac{N_0}{N}}{0.693} \cdot T_{\frac{1}{2}}$$

$$\text{When } N = \frac{N_0}{10}, \ \ln \frac{N_0}{N} = \ln 10 = 2.3 \tag{8.11}$$

$$t = \frac{2.3}{0.693} \cdot T_{\frac{1}{2}} = 3.32 T_{\frac{1}{2}}$$

A radioactive source decays to one-tenth its original value in 3.32 times its half-life. For U235, for example, $T_{\frac{1}{2}} = 7.1 \times 10^8$ years. Therefore, U235 decays to one-tenth its size in

$$\begin{aligned} t_{\text{U235}} &= 3.32 \times 7.1 \times 10^8 \text{ years} \\ &= 23.57 \times 10^8 \text{ years} \\ &= 2357 \text{ million years} \end{aligned}$$

Example 8.4

Radioactive cobalt-60 (Co60) decays to nickel, with a half-life of 5.3 years. What is the value of the decay constant?

$$T_{\frac{1}{2}} = 5.3 \text{ years}$$

From (8.10)

$$\lambda = \frac{0.693}{T_{\frac{1}{2}}} = \frac{0.693}{5.3} = 0.131$$

The activity of this source is then

$$\lambda = 0.131\text{N} \quad \text{curies}$$

where N is the number of atoms of the source.

Example 8.5

A radioactive source of strontium 90 will take 93.29 years to decay to one-tenth of its original size. What is the corresponding half-life?

From Eq. (8.11), within Example 8.3,

$$93.29 = \frac{\ln 10}{0.693} \cdot T_{\frac{1}{2}}$$

$$T_{\frac{1}{2}} = \frac{93.29 \times 0.693}{2.3} = 28.1 \text{ years}$$

8.4. Nuclear Radiation

8.4.1. *Forms of radiation*

The main forms of radiation from radioactive sources are:

(a) alpha particles (α)
(b) beta particles (β)
(c) X radiation (X)
(d) gamma radiation (γ)
(e) cosmic radiation
(f) neutrons (n)

$\left.\begin{array}{l}\text{(c)–(f)}\end{array}\right\}$ classed as "ionising radiation"

(a) *Alpha particles*

An alpha particle (α) is a positively charged particle consisting of two protons and two neutrons, like the nucleus of a helium-4 (${}^4_2\text{He}$) atom. It has a mass number 4 and an atomic number 2. Alpha particles are emitted from natural heavy elements such as uranium and radium. This form of radiation has low penetrating power. For example, it will not normally penetrate the skin and is harmful only if swallowed or breathed into the body. The energy of α particles is in the range 4–6 MeV.

(b) *Beta particles*

A beta particle (β) is essentially a fast-moving electron ejected from the nucleus of an atom. It has no significant mass in amu but carries a negative charge. The loss of a β particle causes a nucleus to increase its atomic number by 1 and acquire positive charge, while its mass number is unchanged. Some beta particles have greater penetrating power than alpha particles. They can penetrate the skin but can be stopped by thin layers of metal, water or glass. Like α sources, β sources are also dangerous if ingested or inhaled into the body. The relative penetrative effects of α and β radiation are depicted in Fig. 8.3 [2]. Both α and β particle radiations can be ionising in nature — they can result in removing an electron from its associated proton in the target atom, which causes the target to change its chemical nature.

(c), (d) *Gamma radiation and X radiation*

Gamma radiation (γ) and X radiation (X) are both forms of electromagnetic radiation, like light and radio waves, but of much higher frequency (and hence shorter

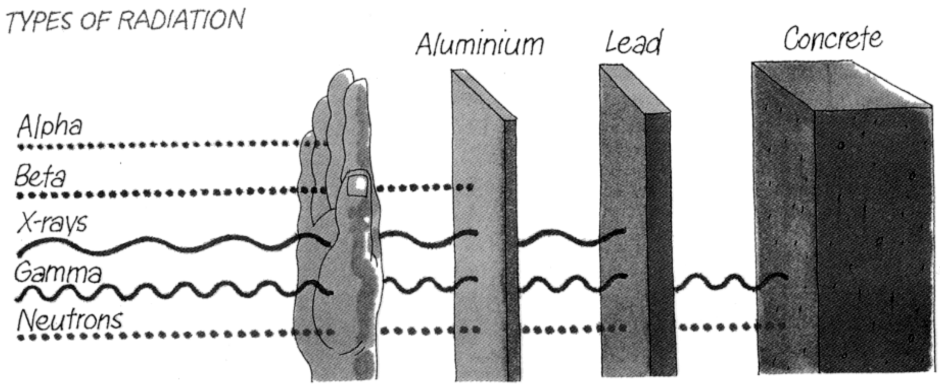


Fig. 8.3. Types of radiation [2] (reproduced by permission of AEA Technology plc).

wavelength). They can also be thought of as beams of photon (quantum) particles, each carrying a discrete package of energy but having negligible mass. The penetrating power of γ radiation is greater than that of X radiation, Fig. 8.3, but it can be screened by sufficient thicknesses of concrete or lead. Gamma radiation may have energy in the range 1–5 MeV. At sufficient dose rates and exposure times, both X-rays and γ-rays can produce ionising effects and be dangerous in human tissue. Ionising radiation impacting the human body does not cause the body to become radioactive.

(e) *Cosmic radiation*

Cosmic radiation consists of a variety of high energy (i.e. low wavelength, high frequency) particles, including protons, that bombard the earth from outer space. They are more intense at higher altitudes than at sea level and constitute a hazard to astronauts in space.

(f) *Neutron radiation*

A beam of neutrons is the most penetrative form of radiation and can be highly dangerous to the human body. In nuclear reactor systems it is necessary to shield the neutrons behind great thicknesses of concrete.

8.4.2. *Units of measurement of radiation*

Of great interest, from the viewpoint of human welfare and safety, is the amount of energy deposited into a material by ionising radiation. This is frequently called the "radiation-absorbed dose", or rad. One rad represents an energy absorption of 10^{-2} J/kg. Another unit now widely used is the Gray (Gy), which represents 100 rads.

The actual quantity of X or γ radiation can be measured in roentgen (R), named after the early pioneer of medical X-rays. One roentgen is the amount of radiation required to produce a specified level of ionisation of air and has a value of

2.58×10^{-4} coulombs/kg. The amount of radiation received, and the energy absorbed due to that radiation, are related by a term known as a "Roentgen equivalent man", or rem. One rem is the amount of radiation, of any type, that produces the same biological effect on human tissue as one rad of gamma or X radiation of a specific energy level. The rem was formerly the international standard unit of radiation exposure level. Since the rem represents a rather large unit of radiation, with regard to human toleration, it is common to use the term millirem (mrem) — 1000th part of a rem. For large radiation dosages it may be more convenient to use the unit sievert (Sv), which is 100 rems.

8.4.3. *Effects of nuclear radiation*

For low levels of radiation exposure the biological effects are so small they cannot be detected. Radiation protection standards assume, however, that the effect is directly proportional to the dose, even at low levels. According to this "linear" theory of radiation effects, if the dose is halved the effect, or the risk of any effect, is halved [3]. Some information on nuclear radiation doses and their effects is given in Table 8.1 [4].

Table 8.1. Effects of nuclear radiation doses [4].

2 mSv/year	Typical background radiation experienced by everyone (av 1.5 mSv in Australia).
2.4 mSv/year	Average dose to US nuclear industry employees.
up to 2.5 mSv/year	Average dose to Australian uranium miners.
up to 5 mSv/year	Typical incremental dose for aircrew in middle latitudes.
9 mSv/year	Exposure by airline crew flying the New York-Tokyo polar route.
10 mSv/year	Maximum actual dose to Australian uranium miners.
20 mSv/year	Current limit (averaged) for nuclear industry employees and uranium miners.
50 mSv/year	Former limit for nuclear industry employees and U miners. Lowest level at which any increase in cancer is evident. It is also the dose rate which arises from natural background levels in several places. Above this, the probability of cancer occurrence (rather than the severity) increases with dose.
350 mSv in lifetime	Criterion for relocating people after the 1986 Chernobyl accident.
1000 mSv	as a dose accumulated over some time, 1000 mSv would probably cause a fatal cancer many years later in 5 of every 100 persons exposed to it (i.e. if the normal incidence of fatal cancer were 25%, this dose would increase it to 30%).
1000 mSv	as short term dose: cause (temporary) radiation sickness such as nausea and decreased white blood cell count, but not death. Above this, severity of illness increases with dose.
5000 mSv	as short term dose: would kill about half those receiving it within a month.
10,000 mSv	as short term dose: fatal within few weeks.

Note: 1 mSv = 100 mrems

The International Commission on Radiological Protection (ICRP) has set a recommended maximum radiation dose, for the general public, at 0.5 rem (500 mrem or 5 mSv) per year from all sources. This is a very conservative rating, containing (necessarily) a large factor of safety [2].

Our knowledge of radiation effects is derived primarily from groups of people who have received high doses. Radiation protection standards assume that any dose of radiation, no matter how small, involves the possibility of risk to human health. However, scientific evidence does not indicate any cancer risk or immediate effects at doses below 100 mSv per year. At low levels of exposure, the body's mechanisms seem to be adequate to repair radiation damage to cells soon after it occurs [4].

8.4.4. *Sources and amounts of nuclear radiation*

The total radiation received from radioactive sources is composed of many forms of natural radiation and man-made radiation.

8.4.4.1. *Natural radiation sources*

There are several sources of natural radiation:

(a) Radiation from space.

(b) Terrestrial radiation proceeding outwards from rocks and soil. In SE England the terrestrial dose rate is about 40–50 mrems/year, whereas in Aberdeen, Scotland, about 500 miles north, it is 80–100 mrems/year due to granite rocks.

Where the soil has a high content of uranium or thorium, as in parts of India or Brazil, the background dose rates are very much higher than in the UK.

(c) Natural radiation within the body due to small traces of radioactive potassium (K40).

(d) Small amounts of radium in the drinking water and food chains.

(e) Small amounts of radioactive carbon in the air. The average dose from natural sources in the UK, including ingested or inhaled components, is about 200 mrems/year (2 mSv/year).

8.4.4.2. *Man-made sources*

Radioactive sources of radiation include the following items:

(f) Some building materials, such as granite or concrete.

(g) Luminous watch dials.

(h) Television and computer screens.

(i) X-ray machines and scanners used for medical diagnosis. These contribute an average of 50 mrems/year to UK residents. For example, a chest X-ray gives about 20 mrems/year.

(j) Gamma radiation sources used in the radiotherapy treatment of cancer.

(k) Nuclear-powered space vehicles, satellites and sea-buoys.

(l) Radioactive debris in the atmosphere caused by nuclear weapons testing and past nuclear bombs. This is estimated to be less than 1 mrem/year.

(m) Nuclear power stations and radioactive waste disposal sites. These are subjected, by law, to the most scrupulous screening and testing by independent inspectors. During normal operation of a nuclear power plant the radiation effect on the public is negligible. In Europe and North America the activities of the nuclear power industry create an average radiation dose of 0.3 mrem/year — less than the radiation from a TV screen.

8.4.5. *Uses of nuclear radiation*

8.4.5.1. *Geological dating*

The radioactive decay of the natural element uranium-238 (U238) has a half-life of 4600 million years, which provides a basis for measuring the age of ancient rock formations. U238 decays, via α and β particle emission, through a chain that successively forms radium, radon, polonium and finally lead-206, an isotope which is not radioactive but is known to descend from radioactive parents. The age of a rock formation can be estimated by measuring the amount of lead-206.

8.4.5.2. *Archaeological dating*

Carbon dioxide in the air is assimilated into all living plants by photosynthesis and ingested by all plant-eating animals and other animals that feed on plant-eating animals (including humans). The atmospheric carbon dioxide contains small amounts of the radioactive isotope carbon-14 (C14), which decays with a half-life of 5600 years. After its death an animal or plant does not ingest any further carbon and the existing C14 then decays without replacement. The ratio of C14 to regular carbon then slowly decreases and provides a time-clock for estimating the age of dead organic materials, up to a few thousand years.

It should be noted that the C14 dating method must not be regarded as infallible. Carbon-14 is not homogeneously distributed among today's plants and animals. For example, volcanic carbon dioxide is known to suppress the C14 level of nearby vegetation. In addition to spatial variations there are temporal variations. The injection of C14-free carbon dioxide into the air through smoke stacks suppresses the level, while an excess of man-made C14 is injected into the atmosphere by nuclear weapons tests.

8.4.5.3. *Medical tracer elements*

One of the medical uses of radioactive materials is as tracer elements for diagnosis. A radioactive material such as cobalt-60 (Co60) is introduced into the patient's suspect organ, which is then examined by X-rays. Patients with digestive tract problems may be fed a "bismuth meal", which enables the whole tract to be examined in order to localise the diagnosis.

8.4.5.4. *Small nuclear power packs*

Heat from the radioactive decay of plutonium-238 ($T_{\frac{1}{2}} = 88$ years) forms the basis of long-lived nuclear batteries. Applications include heart pacemakers, navigational beacons and space satellites and vehicles. The US *Apollo* space missions used plutonium-powered batteries for equipment on the moon's surface. Deep space results, like the *Voyager* spacecraft pictures from Jupiter and Saturn, were also energised from on-board nuclear-powered batteries.

8.4.5.5. *Biological effects on human tissue*

Radiation which causes ionisation within human tissue can have very serious effects. This depends, to some extent, on the intensity of the radiation and the time-scale over which exposure occurs.

Every cell of the body contains molecules of deoxyribonucleic acid (DNA) which store genetic information and control cell growth, function, development and reproduction. It is possible for radiation to damage the DNA so as to cause cell death or some harmful transformation (mutation). Slight injury to a chromosome may alter one or more of the inheritance characteristics passed on to the next generation. Gross chromosome injury would be likely to cause injury or death to the foetus of a pregnant woman. Hospital X-ray procedures are not normally carried out on pregnant patients for this reason.

Exposure to a large radiation dose, within a short time span, causes massive cell destruction. A whole body radiation dose of hundreds of rems in a few minutes causes damage to internal organs, blood cells and bone tissue such that death is likely to follow within weeks. At radiation doses of thousands of rems death is almost certain to follow within a few days. The highly destructive effects of radiation upon cell structure are used in cancer radiotherapy to try and limit or destroy cancerous tissue.

Exposure to repeated doses of low-level radiation can be insidious because the early sickness symptoms of high-level exposure do not occur. If the exposures are widespread in time, then the natural healing of any ill-effects may mitigate any cumulative effect, but some damage may still occur. It is established that overexposure to low-level radiation can cause cancer of various types in humans and shorten the life-span of experimental animals. Delayed hereditary defects have been discovered in animals but not yet in humans. Nevertheless, with the radiation exposure of much of the world population increasing, the possibility of widespread though small genetic abnormalities poses a disturbing uncertainty.

Workers employed in hospital radiology departments, the nuclear industry and other parts of industry dealing with radioactive sources are a special case. Through proper training, protective clothing and practised safe working procedures they may, paradoxically, be safer from radiation exposure than the general public.

8.5. Nuclear Reactors

A nuclear power station for generating electricity is similar in most respects to a coal-, natural-gas- or oil-fired station. Intense heat derived from the primary fuel (coal, gas, oil or uranium) is used to convert water into steam, which drives a turbine–generator system, as in Fig. 1.5 of Chapter 1. In a nuclear reactor the heat source is nuclear fission, described in Sec. 8.2.1 above, using uranium or plutonium as a fuel.

A great, possibly the greatest, advantage of the use of nuclear power is that no fossil fuels are burned and therefore no "greenhouse" gases such as carbon dioxide are emitted. The significance of this depends on the issue of global warming — is it a reality, a dangerous reality or a scientific misconception?

8.5.1. *Thermal (fission) reactors*

Natural uranium contains only 0.7% of fissionable U235. The remainder of the material, 99.3% by weight, consists of the uranium isotope U238, which absorbs neutrons without much fissioning, plus a tiny amount (0.0055%) of U234. For use in some types of nuclear reactor the natural uranium is industrially processed to enrich it so that it contains 2–3% of U235.

To produce a continuous heat source the neutrons released by fission, illustrated in Fig. 8.1, must strike other U235 nuclei, causing further fission in a so-called chain reaction. A sustainable chain reaction requires the presence of a certain minimum or critical mass of U235, configured in some particular design manner. In addition to a source of neutrons, a sustainable chain reaction requires that the rates of neutron production and heat generation be controlled. Also, it is necessary to slow down the velocities of the neutron products of fission by containing them in an enclosure with a moderator material, which is usually ordinary water, heavy water or graphite. Because the purpose of the reactor is heat generation, it is often called a thermal reactor.

For every unit of electrical output power MW_e required from the generator it is necessary to create about three times this value in thermal power MW_{th} in the nuclear reactor.

The principle of a boiling water nuclear reactor core is illustrated in Fig. 8.4 [5]. The nuclear fuel, usually uranium oxide (U_3O_8), is enclosed in metal cans or fuel rods and can be replaced when the active material is spent. Control rods (not the same as fuel rods) of a highly neutron absorbent material such as boron or cadmium can be raised or lowered within the core and these control the rate of fission reaction and hence the heat production When the control rods are fully inserted into the core

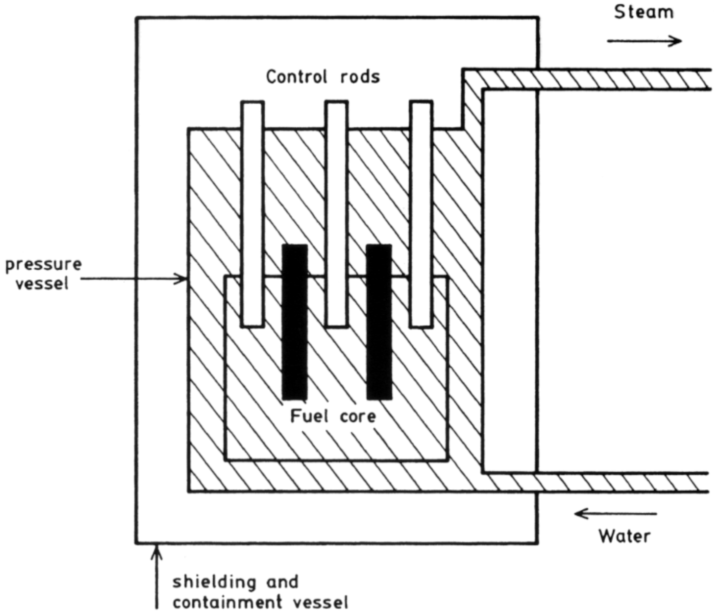

Steam
Control rods
pressure vessel
Fuel core
Water
shielding and containment vessel

Fig. 8.4. Basic form of Boiling Water Reactor [5].

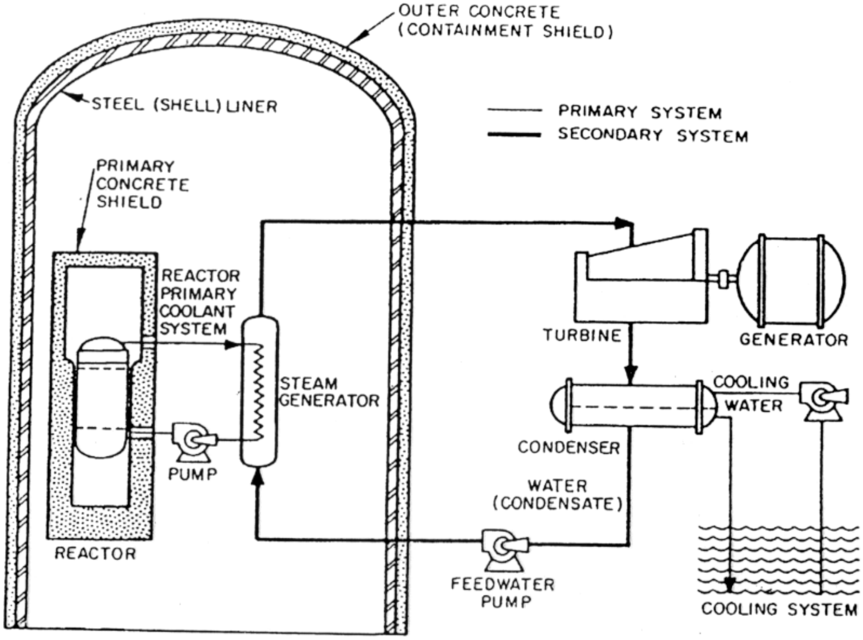

OUTER CONCRETE (CONTAINMENT SHIELD)
STEEL (SHELL) LINER
PRIMARY SYSTEM
SECONDARY SYSTEM
PRIMARY CONCRETE SHIELD
REACTOR PRIMARY COOLANT SYSTEM
STEAM GENERATOR
PUMP
REACTOR
TURBINE
GENERATOR
COOLING WATER
CONDENSER
WATER (CONDENSATE)
FEEDWATER PUMP
COOLING SYSTEM

Fig. 8.5. Pressurised Water Reactor (PWR) system (courtesy of the Westinghouse Corporation, USA).

they absorb neutrons like a dry sponge absorbs water and can, if required, shut the reactor down.

For all types of reactors, the heat from the core has to be extracted and transferred to the steam circuit of the turbo-generator. This is done directly in the Boiling Water Reactor (BWR), where ordinary water (H_2O) is used both as a moderator and as the coolant and heat transfer fluid, Fig. 8.4. The Pressurised Water Reactor (PWR), Fig. 8.5, also uses ordinary water as a moderator but this is enclosed within a separate circuit from the steam circuit [6]. Both the BWR and the PWR use enriched uranium as fuel and are widely used US designs.

In the UK the older range of nuclear reactors are called Magnox reactors, because the fuel is natural uranium clad in magnesium alloy cans with low neutron absorption. Graphite is used as a moderator within the core and heat is transferred to the external heat exchangers using high-pressure carbon dioxide (CO_2) gas. More recent nuclear stations in the UK use the Advanced Gas-Cooled Reactor (AGR) design. This is similar, in principle, to the Magnox design but uses uranium fuel enriched to 2.3% content of U235. The fuel enrichment permits higher operational temperature and heat output than a Magnox type, requiring a smaller reactor core, and resulting in a more efficient steam cycle.

A particularly elegant and successful design is the Pressurised Heavy Water CANDU reactor (PHWR) developed at Chalk River, Ontario, Canada. This uses natural uranium as fuel and high-pressure heavy water (D_2O) as a moderator and heat transfer fluid. A comparison of some of the design details of various types of thermal reactors is given in Table 8.2 [7].

Historically the world's first reactor to be connected to an electricity supply network was a Magnox reactor in England in 1953. Britain and France attempted

Table 8.2. Performance data of thermal reactors [7].

Reactor	Magnox (UK) 600 MW_e	BWR (USA) 600 MW_e	PWR (USA) 700 MW_e	PHWR (CANDU) (Canada) 600 MW_e	AGR (UK)
Uranium Enrichment % uranium-235	0.7 (natural)	2.6	3.2	0.7 (natural)	2.3
Coolant outlet temperature (°C)	400	286	317	305	650
Coolant pressure (1 bf/in^2 absolute)	300	1050	2235	1285	600
Steam cycle efficiency %	31	32	32	30	42
Core diameter (metres)	14	3.7	3	7.1	9.1
Core height (m)	8	3.7	3.7	5.9	8.5
Moderator	graphite	water	water	heavy water	graphite
Heat transfer fluid	carbon dioxide	water	water	heavy water	carbon dioxide

to make the Magnox gas-graphite design the world standard but this initiative ended in 1967. From the early 1970s until the mid-1980s the world market for reactors was dominated by the US light water PWR system, which was an outgrowth of the American nuclear submarine programme. Only the Canadian CANDU reactor survived as effective opposition [8].

The latest (possibly the final) American nuclear power plant is Watts Bar 1, which opened at Spring City, Tennessee in 1996 [9, 10]. The latest British plant, Sizewell B, which is also a PWR design, rated at 1110 MW_e, went "onstream" in 1995 [11]. No further nuclear plants are under construction or planned in the UK or the USA. But the prospects for nuclear power in the USA are improving. The US Nuclear Regulatory Commission (NRC) recently (2001) granted extensions to operate two reactors 20 years beyond their initial 40-year licences. Other US companies have petitioned the NRC for nuclear plant life extension [12]. Many countries are proceeding with large-scale nuclear programmes, including China, France, India, Japan, Romania, Russia, South Korea, Taiwan and Ukraine. The big future market for nuclear-generated electricity is the fast-growing Asian countries of the Pacific Rim, notably China [12, 13].

In both Britain and the USA, the nuclear industry has failed to convince a sceptical public of the safety and the economic and environmental advantages of nuclear-generated electricity. The French have continued to build nuclear stations so that now (2002) most of the electricity generated in France is from nuclear sources. Some of it is now sold to Britain, using undersea cables under the English Channel.

It remains to be seen which country has chosen the wiser course. France, which has no oil, will eventually become totally nuclear. The USA and the UK are both oil-rich while the oil lasts and coal-rich while the coal lasts. What then?

8.5.2. *Uranium supplies*

Natural uranium has to be mined and there is some uncertainty about the remaining reserve stock and the economic viability of mining it. The overall uranium fuel supply situation depends on whether the uranium oxide (U_3O_8) is used on a "once through" basis only or whether the uranium fuel stock is replenished by nuclear fuel reprocessing. Another option is to implement plutonium as a fuel, obtained through the use of fast breeder reactors described in Sec. 8.5.4 below. A further option is the use of thorium as a fuel.

The nuclear power industry, which largely uses nuclear fission (thermal) reactors, is in recession in the USA and the UK but uranium continues to be needed elsewhere and the demand is growing. It is estimated that there were 437 thermal reactors in operation around the world in 2000, including 33 in the UK and 104 in the USA, Table 8.3 [12]. A listing of the major recoverable resources of uranium oxide is given in Table 8.4 [12]. These stocks tend to deplete year by year but they are

Table 8.3. Status of nuclear power [13].

Source: Reactor data: ANSTO, based on information to 8 August 2000.
Brazil's second reactor started up in July 2000, but was not connected to the grid by 8 August.
Operating = Connected to the grid; Planned = Relatively firm plans or Letter of Intent sent

COUNTRY	OPERATING* at 31/7/00		BUILDING at 31/7/00		ON ORDER or PLANNED		TOTAL	
	No.	$\mathrm{MW_e}$	No.	$\mathrm{MW_e}$	No.	$\mathrm{MW_e}$	No.	$\mathrm{MW_e}$
Argentina	2	935	1	692	0	0	3	1627
Armenia	1	376	0	0	0	0	1	376
Belgium	7	5680	0	0	0	0	7	5680
Brazil	1	626	1	1245	0	0	2	1871
Bulgaria	6	3538	0	0	0	0	6	3538
Canada	18*	12058	0	0	0	0	18	12058
China	3	2079	8	6320	2	1800	13	10199
Czech Rep.	4	1648	2	1824	0	0	6	3472
Egypt	0	0	0	0	1	600	1	600
Finland	4	2656	0	0	0	0	4	2656
France	59	63203	0	0	0	0	59	63203
Germany	19	21107	0	0	0	0	19	21107
Hungary	4	1742	0	0	0	0	4	1742
India	12	2144	4	1304	10	4480	26	7928
Indonesia	0	0	0	0	1	600	1	600
Iran	0	0	1	950	3	2850	4	3800
Japan	53	43505	1	796	14	18288	68	62589
Korea DPR (N)	0	0	0	0	2	1900	2	1900
Korea RO (S)	16	12970	4	3800	10	11200	30	27970
Lithuania	2	2370	0	0	0	0	2	2370
Mexico	2	1308	0	0	0	0	2	1308
Netherlands	1	452	0	0	0	0	1	452
Pakistan	2	425	0	0	0	0	2	425
Romania	1	650	1	620	0	0	2	1270
Russia	29	19843	3	2825	9	7450	41	30118
Slovakia	6	2472	0	0	0	0	6	2472
Slovenia	1	620	0	0	0	0	1	620
South Africa	2	1842	0	0	0	0	2	1842
Spain	9	7345	0	0	0	0	9	7345
Sweden	11	9445	0	0	0	0	11	9445
Switzerland	5	3170	0	0	0	0	5	3170
Taiwan	6	4884	2	2600	0	0	8	7484
Ukraine	14	12120	2	1900	0	0	16	14020
UK	33	12518	0	0	0	0	33	12518
USA	104	98015	0	0	0	0	104	98015
WORLD	437	351,746	30	24,876	52	49,168	519	425,790

*Total includes 4 laid up Canadian Pickering A reactors totalling 2060 $\mathrm{MW_e}$.

Table 8.4. Estimated recoverable resources of uranium [13] (tonnes U_3O_8, % of world).

Australia	889 000	27%
Kazakhstan	558 000	17%
Canada	511 000	15%
South Africa	354 000	11%
Namibia	256 000	8%
Brazil	232 000	8%
Russian Fed.	157 000	5%
USA	125 000	4%
Uzbekistan	125 000	4%
World Total	**3 340 000**	

Reasonably Assured Resources plus Estimated Additional Resources - category I, to US$ 80/kg U, from *Uranium: Resources, Production and Demand 1999*, OECD NEA & IAEA, July 2000.
Brazil, Kazakhstan and Russian Figures above are 75% of in situ totals.

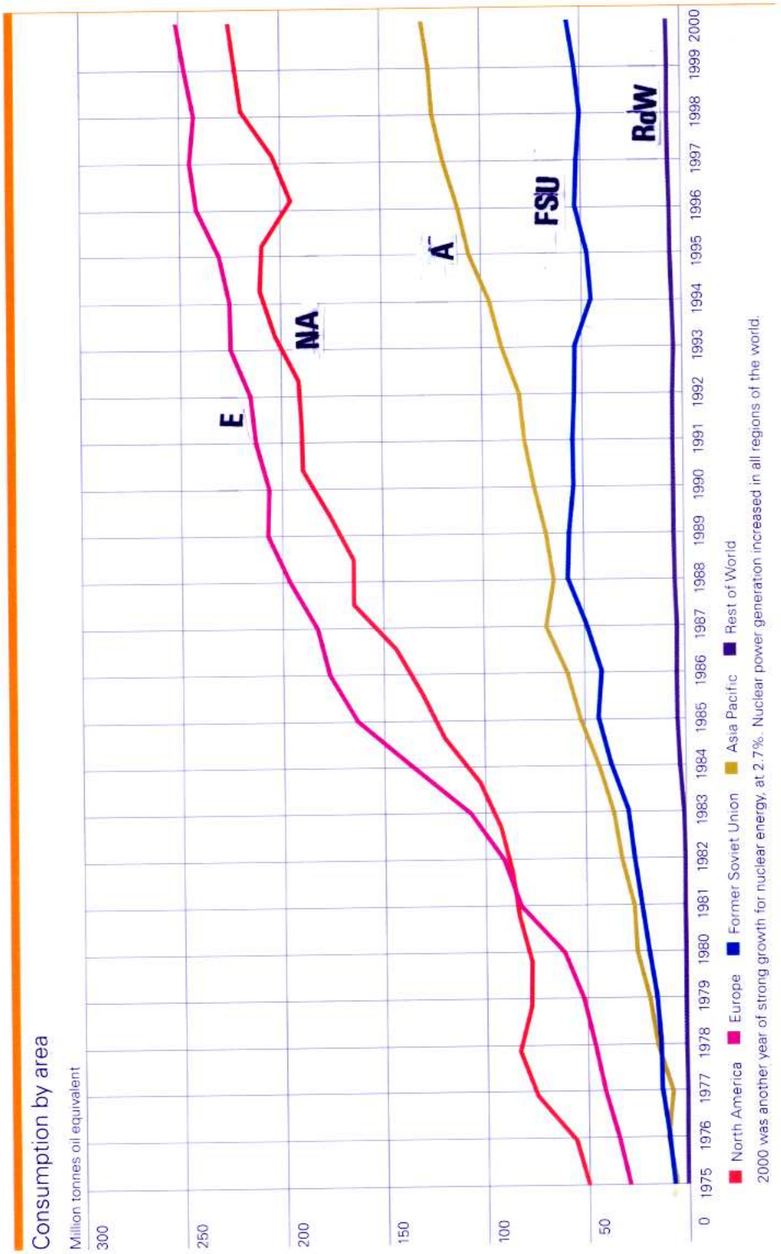
widely distributed geographically and are in accessible locations. The world demand for nuclear-generated electricity continues to increase in most areas, Fig. 8.6 and Table 8.5 [14, 15].

There is no reliable data upon which one can accurately forecast a lifetime expectation of continued natural uranium supply. It is being used up and is not renewable. Even if major untapped deposits are found it is evident that the world uranium supplies will be exhausted long before the coal supplies. A pessimistic forecast would be that the uranium will not even outlast the oil. If nuclear fission (thermal) reactors are to continue to be used for electricity generation it is inevitable that this will require the widespread use of uranium fuel reprocessing and also the development of advanced forms of fast breeder reactor. This will, in turn, increase the amount of nuclear waste — an issue that is discussed in Sec. 8.6 below.

8.5.3. *Plutonium*

Figure 8.7 shows the continuation of the nuclear fission process illustrated in Fig. 8.1. This results in the production of radioactive plutonium 239 (Pu239), which is an artificial chemical element isotope that does not occur in nature. Plutonium is a metal, hard and brittle like cast iron, that can be melted, moulded and machined. It can also be soft alloyed with other metals to produce wire and metal foil. Other plutonium isotopes exist, notably Pu238, Pu240 and Pu241, all of which are radioactive. Plutonium is highly radiotoxic and must be used under strictly controlled and guarded conditions [16].

In a thermal reactor the Pu239 content is fissioned by neutron capture and contributes about one third of the heat generated by the overall uranium fission process, at the same time releasing further neutrons. The fissioning of Pu239 also



2000 was another year of strong growth for nuclear energy, at 2.7%. Nuclear power generation increased in all regions of the world.

Fig. 8.6. Consumption of nuclear-generated electricity [15].

Table 8.5. World consumption of nuclear-generated electricity (mtoe) [15].

oil natural gas coal **nuclear energy** hydroelectricity primary energy

Consumption*

Million tonnes oil equivalent	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	**2000**	Change 2000 over 1999	2000 share of total
USA	156.7	166.4	168.1	165.8	173.9	182.9	183.2	170.7	183.0	197.8	**204.7**	3.5%	30.6%
Canada	18.8	21.9	20.8	24.2	27.8	25.2	23.9	21.3	18.5	19.0	**18.7**	–1.3%	2.8%
Mexico	0.8	1.1	1.0	1.3	1.1	2.2	2.0	2.7	2.4	2.6	**1.8**	–28.9%	0.3%
Total North America	176.3	189.4	189.9	191.3	202.8	210.3	209.1	194.7	203.9	219.4	**225.2**	2.7%	33.7%
Argentina	1.9	2.0	1.8	2.0	2.1	1.8	1.9	2.1	1.9	1.8	**1.6**	–13.0%	0.2%
Brazil	0.6	0.4	0.5	0.1	†	0.7	0.6	0.8	0.8	1.0	**1.4**	39.4%	0.2%
Chile	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Colombia	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Ecuador	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Peru	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Venezuela	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Other S. & Cent. America	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Total S. & Cent. America	2.5	2.4	2.3	2.1	2.1	2.5	2.5	2.9	2.7	2.8	**3.0**	5.8%	0.4%
Austria	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Belgium & Luxembourg	11.0	11.1	11.2	10.8	10.5	10.7	11.2	12.2	11.9	12.7	**12.7**	0.5%	1.9%
Bulgaria	3.8	3.4	3.0	3.6	4.0	4.5	4.7	4.6	4.2	3.9	**4.9**	25.1%	0.7%
Czech Republic	3.2	3.1	3.2	3.3	3.3	3.2	3.3	3.2	3.4	3.4	**3.5**	1.7%	0.5%
Denmark	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Finland	4.9	5.0	4.9	5.1	5.0	4.9	5.1	5.4	5.7	6.0	**6.2**	3.9%	0.9%
France	81.0	85.5	87.3	95.0	92.9	97.3	102.5	102.0	100.1	101.9	**107.3**	5.3%	16.0%
Germany	39.3	38.1	41.0	39.6	39.0	39.8	41.7	43.9	41.7	43.9	**43.8**	–0.2%	6.6%
Greece	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Hungary	3.5	3.5	3.6	3.6	3.6	3.6	3.7	3.6	3.6	3.6	**3.7**	0.6%	0.6%
Iceland	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Republic of Ireland	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Italy	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Netherlands	0.9	0.9	1.0	1.0	1.0	1.0	1.1	0.6	1.0	1.0	**1.0**	2.4%	0.2%
Norway	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Poland	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Portugal	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Romania	–	–	–	–	–	–	0.4	1.4	1.4	1.3	**1.4**	5.0%	0.2%
Slovakia	3.1	3.0	2.9	3.1	3.1	3.0	2.9	2.8	2.9	3.4	**4.3**	25.7%	0.6%
Spain	14.0	14.3	14.4	14.5	14.3	14.3	14.5	14.3	15.2	15.2	**16.0**	5.5%	2.4%
Sweden	17.6	19.8	16.4	15.8	18.9	18.1	18.9	18.0	18.2	18.9	**14.8**	–21.5%	2.2%
Switzerland	6.1	5.9	6.1	6.0	6.3	6.4	6.5	6.6	6.7	6.4	**6.8**	6.1%	1.0%
Turkey	–	–	–	–	–	–	–	–	–	–	**–**	–	–
United Kingdom	17.0	18.2	19.8	23.1	22.8	23.0	24.4	25.3	25.8	24.8	**24.0**	–3.5%	3.6%
Other Europe	1.2	1.3	1.0	1.0	1.2	1.2	1.2	1.3	1.3	1.2	**1.2**	1.3%	0.2%
Total Europe	206.6	213.1	215.8	225.5	225.9	231.0	242.1	245.2	243.1	247.6	**251.6**	1.6%	37.6%
Azerbaijan	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Belarus	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Kazakhstan	–	0.1	0.1	0.1	0.1	†	†	0.1	†	–	**–**	–	–
Lithuania	4.4	4.4	3.8	3.2	2.0	3.1	3.6	3.1	3.5	2.5	**2.2**	–14.6%	0.3%
Russian Federation	30.5	31.0	30.9	30.8	25.2	25.6	28.1	27.9	26.9	30.9	**33.7**	8.8%	5.0%
Turkmenistan	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Ukraine	19.7	19.4	19.0	19.4	17.8	18.2	20.5	20.5	19.4	18.6	**19.9**	7.2%	3.0%
Uzbekistan	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Other Former Soviet Union	–	–	–	–	–	0.1	0.6	0.4	0.4	0.6	**0.5**	–11.5%	0.1%
Total Former Soviet Union	54.6	54.9	53.8	53.5	45.1	47.0	52.8	52.0	50.2	52.6	**56.3**	6.9%	8.4%
Iran	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Kuwait	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Qatar	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Saudi Arabia	–	–	–	–	–	–	–	–	–	–	**–**	–	–
United Arab Emirates	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Other Middle East	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Total Middle East	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Algeria	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Egypt	–	–	–	–	–	–	–	–	–	–	**–**	–	–
South Africa	2.3	2.5	2.5	2.0	2.6	3.1	3.2	3.4	3.7	3.5	**3.5**	1.3%	0.5%
Other Africa	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Total Africa	2.3	2.5	2.5	2.0	2.6	3.1	3.2	3.4	3.7	3.5	**3.5**	1.3%	0.5%
Australia	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Bangladesh	–	–	–	–	–	–	–	–	–	–	**–**	–	–
China	–	–	0.1	0.4	3.6	3.3	3.7	3.7	3.9	3.8	**4.3**	12.8%	0.7%
China Hong Kong SAR	–	–	–	–	–	–	–	–	–	–	**–**	–	–
India	1.7	1.4	1.7	1.6	1.3	2.0	2.2	2.6	2.9	3.3	**4.1**	23.9%	0.6%
Indonesia	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Japan	50.5	54.0	56.2	64.1	66.9	74.3	76.8	83.0	84.4	82.0	**82.5**	0.7%	12.4%
Malaysia	–	–	–	–	–	–	–	–	–	–	**–**	–	–
New Zealand	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Pakistan	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	†	**0.1**	>100.0%	†
Philippines	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Singapore	–	–	–	–	–	–	–	–	–	–	**–**	–	–
South Korea	13.6	14.5	14.6	15.0	15.1	17.3	19.1	19.9	23.1	26.6	**28.1**	5.7%	4.2%
Taiwan	8.5	9.1	8.7	8.9	9.0	9.1	9.7	9.4	9.5	9.9	**9.9**	0.2%	1.5%
Thailand	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Other Asia Pacific	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Total Asia Pacific	74.4	79.1	81.4	90.1	96.1	106.1	111.6	118.7	123.9	125.6	**129.0**	2.8%	19.4%
TOTAL WORLD	**516.7**	**541.4**	**545.7**	**564.5**	**574.6**	**600.0**	**621.3**	**616.9**	**627.5**	**651.5**	**668.6**	**2.7%**	**100.0%**
of which: OECD	438.9	463.3	469.6	488.2	502.4	524.2	537.9	532.7	544.7	565.8	**575.6**	1.8%	86.1%
European Union 15	185.7	192.9	196.0	204.9	204.4	209.1	219.4	221.7	219.6	224.4	**225.8**	0.7%	33.8%
Other EMEs‡	15.1	15.5	15.4	15.1	18.8	20.1	21.4	22.1	22.8	23.3	**24.9**	6.9%	3.7%

*Converted on the basis of the average thermal efficiency of a modern nuclear power plant (i.e. 33% efficiency).

†Less than 0.05.

‡Excludes Central Europe and Former Soviet Union.

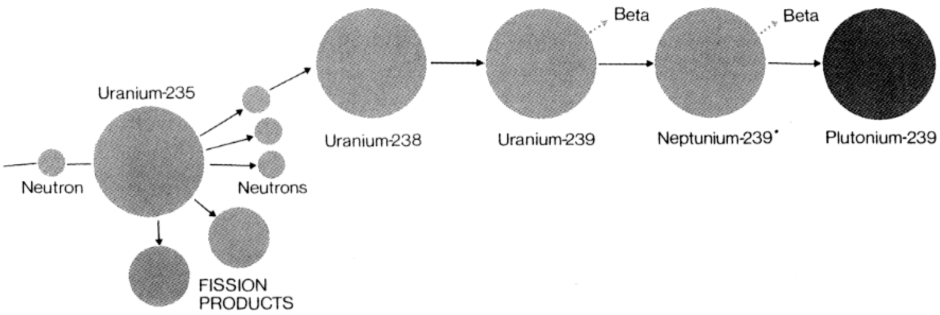


Fig. 8.7. The formation of plutonium [16] (reproduced by permission of AEA Technology plc).

creates radioactive fission products similar to those from uranium and these form part of the nuclear waste of the reactor cycle. The significance of the use of plutonium for nuclear-electric generation is largely in fast breeder reactors, described in the following section.

8.5.4. *Fast breeder reactors*

To produce a neutron chain reaction in a thermal nuclear reactor requires that the neutrons be slowed down by a moderator before they will fission the atom of U235 in the fuel. In both natural uranium and enriched uranium fuels, the proportion of U235 atoms is small and only a tiny part of the energy available from the uranium can be exploited. The abundant component of natural uranium (99.3%) is U238, which absorbs neutrons from the fission of U235 atoms, Fig. 8.7, to produce fissionable Pu239. Most of this plutonium remains unused in a thermal reactor cycle but can be subsequently separated out by reprocessing of the nuclear waste.

Great enhancement of a nuclear reactor heat generation capability is obtained by the use of fuel which contains 20–30% plutonium plus 80–70% uranium. This fuel is rich in atoms that can be fissioned by fast neutrons. A chain reaction can be sustained without the use of a moderator and the "fast reactor" core is much smaller than a thermal reactor core, being of the order of 1–4 cubic metres. As the plutonium in the core is consumed for electricity generation, the neutrons released by its fission are absorbed into a surrounding blanket of U238, thereby creating more plutonium. The process therefore breeds plutonium and the reactor is commonly known as a "fast breeder reactor" or just "breeder reactor". By appropriate design, the amount of plutonium produced from the uranium can be made less than or equal to or greater than the original plutonium source. Utilisation of the U238 in a breeder reactor is about 60 times more efficient than that of a thermal reactor [17].

The basic structure of a fast breeder reactor is shown in Fig. 8.8 [6]. Its operation is similar, in principle, to that of the thermal reactors described in Sec. 8.5.1. Liquid sodium, used as a coolant and heat transfer fluid, is more efficient than the water

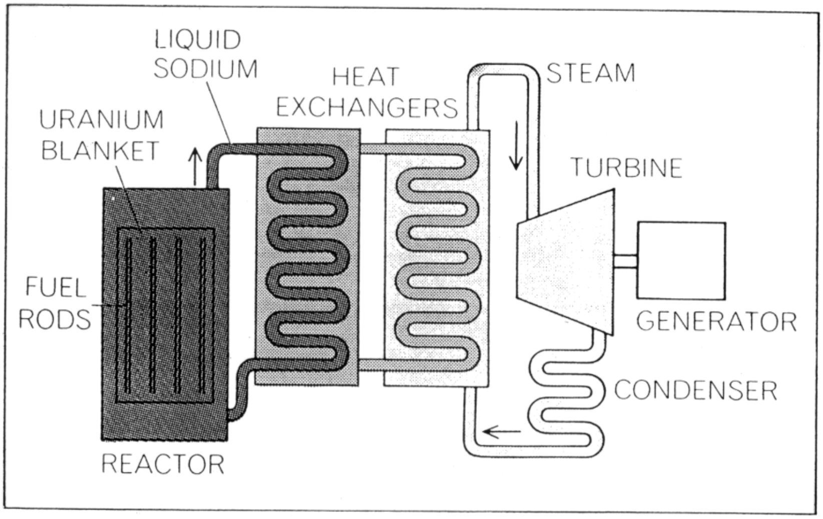


Fig. 8.8. Configuration of a fast breeder reactor [6].

or gas of thermal reactors. The sodium becomes radioactive, with $T_{\frac{1}{2}} = 15$ hours, so that the radiation decays to insignificance about 14 days after plant shutdown. The fuel cans and uranium blanket need to be replaced about once a year. Newly created plutonium is separated out and can be reused.

Much of the pioneering work on fast breeder reactors took place in the UK. A fast reactor started up at Dounreay in Scotland in 1959 and ran until 1977. Its successor, the Prototype Fast Reactor (PFR), rated at 250 MW_e, has been in operation since 1974 [8]. The Phoenix reactor in France, also rated at 250 MW_e, started up in 1974 and was succeeded by super-Phoenix, a 1200 MW_e commercial size reactor. At present (2002) super-Phoenix is only permitted to operate at low power for experimental reasons. Fast reactor development programmes have been considered in Germany, Japan, Russia and the USA. The cost of building a liquid-metal fast breeder reactor is higher than that of a thermal reactor of the same rating because of the need for finer engineering tolerances, adequate systems to safeguard the use of liquid metals such as radioactive sodium and also the costs of using, transporting and processing the hazardous fuel materials, notably plutonium.

It is the authors' view that the use of nuclear fission with fuel breeding represents one of the four great long-term energy options for the world, as discussed in Chapter 14.

8.5.5. *Reactor safety*

A nuclear reactor that is designed for electricity generation cannot explode like an atomic bomb. The fissile material in the core is insufficiently concentrated and too small in mass. Acts of deliberate sabotage might render a nuclear power station inoperable as a producer of power but could not convert it into a bomb. Also, the nuclear materials, usually uranium and/or plutonium, are not present in the form that would be directly usable in nuclear weapons.

The nuclear risks attendant in reactor operation are:

(a) failure of the steel pressure vessel or even meltdown of the core due to loss/lack of coolant,
(b) escape of radioactive material into the surrounding environment,
(c) nuclear waste.

The engineering control systems for nuclear reactor operation are invariably duplicated and sometimes triplicated to sidetrack any equipment failures. Duplicated systems may have the additional safety feature that they overlap each other and work on alternative features. For example, the presence of reactor coolant, within a totally enclosed pressure vessel, can be sensed using its temperature and pressure independently.

All reactor controls are designed to operate on a "fail-safe" basis. If the electricity driving the coolant pumps or heat transfer system is cut off, even from the plant standby supplies, the control rods fall under gravity into the core, Fig. 8.4, and shut the reactor down. The reactor core, contained in a steel pressure vessel, is itself located within a very thick biological shield of concrete, Fig. 8.5.

The operation of nuclear reactors is subjected to the most rigorous engineering design tolerances and to extremely stringent safety management systems. Standard safety features include the monitoring and measurement of all the physical and chemical properties of reactor materials. There is an emergency core-cooling system. Key features of a nuclear reactor system are kept in physical separation to minimise any damage due to fire or flood.

8.5.6. *Nuclear reactor accidents*

In spite of all the precautions, reactor accidents happen. For example, the consequence of significant loss of coolant is catastrophe. In the presence of inadequate cooling, the core temperature rises rapidly. Risk exists of explosion of the pressure vessel container, which would release radioactive liquid or gas into the local environment. Slight risk also exists that the reactor core could "melt down" into a molten mass that might even burn its way through the steel container and concrete into the ground below the reactor building. It would thereby become a highly dangerous source of uncontained radioactive radiation. The local heat generated by the radiation from an uncontained core would be intense and likely to increase the spread of radiation by water, steam or gas escapes. There has never been a serious reactor coolant or containment failure nor any reactor meltdown in the UK or France.

8.5.6.1. *Three Mile Island*

A serious accident occurred to a 956 MW_e, PWR reactor at Three Mile Island, Harrisburg, Pennsylvania, USA in 1979. About an hour after a reactor was shut down out of service, a serious loss of coolant occurred due to an opened relief valve but was not noticed. Auxiliary feedwater pumps failed to circulate the necessary water due to valves that had been closed to facilitate routine repairs and maintenance. Some other serious operational errors were made. The severely damaged reactor core became exposed with radioactive leakage into the surrounding environment [18]. There was no fatality or serious injury due to the accident at Three Mile Island, either to the workers in the industry or to the public. The Three Mile Island plant is no longer in use. It is noteworthy that this major accident was not due to design errors or equipment failures but to human error — the safety management system was flawed. The consequent bad publicity and loss of confidence in the nuclear industry has played a large part in the effective curtailment of any foreseeable future expansion of nuclear power generation in the USA.

8.5.6.2. *Chernobyl*

The world's worst nuclear accident occurred at Chernobyl in the Ukraine in 1986. At that time a major part of the electricity generated in the then Soviet Union was (and still is) nuclear-based. The standard thermal reactor systems, known as RBMK 1000, rated at 1000 MW_e, are boiling-water, graphite-moderated systems using enriched uranium dioxide and ordinary (light) water cooling, similar in principle to Fig. 8.4. Each reactor system consists of two identical reactors back-to-back, rated at 500 MW_e. In 1986 ten RBMK 1000 units were in service at Chernobyl, with a further eight units under construction.

On 25 April 1986 preliminary actions were begun prior to an experiment to determine if a turbine-generator would still power some reactor cooling pumps while it ran down after its steam supply was removed. The test had a legitimate purpose but was unplanned, unapproved and not properly supervised. As part of the test preliminary procedure the emergency core-cooling system was disconnected for nine hours — in contravention of written safety rules. There followed a series of major operational blunders, over several hours, in which control rod settings were inaccurate, some manual fault-trips were deliberately disengaged and some of the coolant pumps became overloaded so that the cooling water temperature rose to nearly boiling point. A computer printout of the reactor performance that showed the need for immediate manual shutdown, because there were far too few control rods inserted into the reactor, was ignored. The automatic safety system that would have tripped (i.e. shut down) the reactor had been overridden by the operators to facilitate the proposed test. In effect, vital safety procedures were ignored because the experimentalists were under time pressure to complete their work.

On 26 April 1986, just 24 hours after the test procedures began, control rods were withdrawn and the coolant flow reduced to increase the reactor power. There was a rapid, exponential rise of reactor power and fuel temperature, generating an enormous steam pressure in the coolant circuit. An alert shift foreman ordered an emergency shutdown but was just too late. The control rods could not be fully lowered in time and the uranium fuel channel ruptured. Two steam explosions occurred, like the bursting of a steam boiler, that blew up the pressure vessel and reactor core and completely destroyed the reactor hall. Burning radioactive debris was thrown into the air and fires were started. There was massive escape of highly radioactive gas and steam that contaminated the ground area up to about 20 miles around the site. The local city of Pripyat, 116,000 people, was totally evacuated. The ancient and large city of Kiev, 80 miles away, escaped major radioactive contamination because the prevailing winds did not blow for several days [19].

The accident destroyed the Chernobyl-4 reactor and killed 31 people, including 28 from radiation exposure. A further 209 on site were treated for acute radiation poisoning, and among these, 134 were confirmed (all of whom recovered). Nobody off-site suffered from acute radiation effects. However, large areas of Belarus, Ukraine, Russia and beyond were contaminated in varying degrees. The Chernobyl accident is the only case in the history of commercial nuclear power where radiation-related fatalities have occurred. There have been fatalities in military and research reactor contexts [20].

Several organisations have reported on the impacts of the Chernobyl accident, but all have found difficulties in assessing the significance of what they have observed because of the paucity of reliable information on public health matters prior to 1986. In 1989 the World Health Organisation (WHO) first raised concerns that local medical scientists had incorrectly attributed various biological and health effects to radiation exposure.

An International Atomic Energy Agency (IAEA) study involving more than 200 experts from 22 countries and published in 1991 was more substantial. In the absence of pre-1986 data it used a control population to compare those exposed to radiation. They found significant health disorders in both control and exposed groups, but at that stage none was radiation-related.

Studies in the Ukraine, Russia and Belarus since have been based on national registers of over one million people possibly affected by radiation. These have confirmed a rising incidence of thyroid cancer among exposed children. Late in 1995, the WHO linked nearly 700 cases of thyroid cancer among children and adolescents to the Chernobyl accident, and among these some ten deaths are attributed to radiation from it [21].

So far (2002) no increase in leukaemia is discernible, but this is expected to be evident in the next few years along with a greater, though not statistically discernible, incidence of other cancers. There has been no increase attributable to Chernobyl in congenital abnormalities, adverse pregnancy outcomes or any other radiation-induced disease in the general population either in the contaminated areas or further afield [20].

Chernobyl was a horror story come to life. It is significant to note, however, that it was not the machines that failed but the operators and designers. With better training, better plant management and strict insistence on safety procedures, it would not have happened. The nuclear industry in Britain, which is particularly well organised and well run, insist that it could not happen in the UK. Most of the electricity generated in the various countries that made up the Soviet Union is still derived from nuclear power and there are no plans to change the situation. The stricken reactor at Chernobyl is now entombed in reinforced concrete, still at its original site.

Suspicions about the safety of early Soviet reactor designs caused much misgiving amongst engineers in the west. Since the Chernobyl accident, the safety of all Soviet-designed reactors has improved vastly, due largely to the development of a culture of safety encouraged by increased collaboration between East and West, and substantial investment in improving the reactors.

Since 1989 over 1000 nuclear engineers from the former Soviet Union have visited Western nuclear power plants and there have been many reciprocal visits. Over 50 twinning arrangements between East and West nuclear plants have been put in place. Most of this has been under the auspices of the Association of Nuclear Operators, a body formed in 1989 which links 130 operators of nuclear power plants in more than 30 countries [20].

8.6. Nuclear Waste [22, 23]

8.6.1. *Sources of waste*

In any section of the chemical and mining industries, the mining, processing and use of the raw material creates waste. In the nuclear industry, the collection, transportation, processing, management, storage and disposal of nuclear waste constitutes the most challenging problem of all. Nuclear waste is radioactive and is obtained by a number of different activities:

(a) uranium mining and purification
(b) fabrication of reactor fuel
(c) nuclear reactor operation
(d) nuclear fuel reprocessing
(e) nuclear reactor decommissioning
(f) nuclear weapons fabrication and testing

(a) *Uranium mining and purification*

Large quantities of waste material are produced at uranium mines. The deep-mined ore is brought to the surface and finely ground or milled to concentrate the uranium. This facilitates the release of radon, a radioactive gas that is part of the decay chain of uranium. The residues from the milling process, known as tailings, still contain 80% of the original radioactivity in the ore. The best treatment of the tailings would be to return them to their original underground mines but this is not economical. In practice the wastes are covered with earth and vegetation, like coal-mining waste. Uranium mining tailings are many times smaller than coal-mining waste for the same amount of generated electricity. There is no uranium mining in the UK.

(b) *Fabrication of reactor fuel*

Purification of the uranium concentrate and its enrichment by adding U235 to fabricate reactor fuel rods and pellets also produces waste. Enrichment plant waste usually consists of liquid effluent containing low levels of decay products.

(c) *Nuclear reactor operation*

The operation of a nuclear reactor results in radioactive fission products, as described in Sec. 8.2. These are all contained in the fuel rods which are themselves contained within the reactor containment system during reactor operation. Some waste is produced by reactions between the neutrons and the coolant and the containment system but these remain inside the reactor until decommissioning. A small quantity of radioactive gaseous effluent is sometimes released but this forms only about 1% of the local natural background radiation.

(d) *Nuclear fuel reprocessing*

The serious hazards of nuclear waste begin when spent fuel rods are removed from the reactor for disposal or, more likely, for reprocessing. Spent reactor fuel is so radioactive that it has to be handled behind thick shielding or water. Waste reprocessing involves dismantling the fuel cans and dissolving the contents in nitric acid to retrieve the reusable uranium and plutonium. There remains a liquid waste containing long-lived radioactive fission products such as strontium 90, caesium 137 and tritium, classed as high-level waste, which is concentrated and cool-stored. Various other wastes include the metal fuel cans and the cooling water or gas. These are classed as intermediate level and are also stored.

(e) *Nuclear reactor decommissioning*

The decommissioning of a nuclear reactor involves either "mothballing" or "entombment", both of which leave the radioactive hazard undisturbed but in need of constant monitoring. Dismantling a reactor, however, would involve handling thousands of tons of highly radioactive material and would be undertaken only after a delay of (say) 50 years to allow the bulk of the radioactivity to decay.

(f) *Nuclear weapons fabrication and testing*

The explosive material in atomic weapons is a fissile form of uranium and/or plutonium. An atomic bomb can be made from about 2 kilogrammes of U233 or Pu239, both of which materials are to be found in spent fuel rods and therefore in nuclear fuel recycling plants. The design, fabrication and testing of atomic weapons inevitably creates high-level waste material that is not all in suitable form for reprocessing.

8.6.2. *Waste disposal*

The principal aims of nuclear waste disposal are to dilute the radioactivity to a harmless level and disperse it to the environment or to isolate the radioactive materials under containment until the radioactivity has decreased to insignificance. For convenience, the waste materials are classified with regard to the level and longevity of the radioactivity as low-level, intermediate-level or high-level. Very low-level liquid and gaseous wastes are disposed of directly into the environment. Some low-level solid wastes such as soiled laboratory clothing that have only slight contamination are packaged into metal drums and buried in landfill sites. Wastes of a slightly higher radioactivity level, but still within the low-level classification, include wastes from hospitals and laboratories. These are encased in concrete and enclosed in steel drums. Such waste from the UK is tipped into the Atlantic Ocean, about 4 km (2 1/2 miles) deep, at an internationally agreed location — about 500 miles off Lands End.

Intermediate-level wastes include reactor fuel cans, fuel fragments, sludges and filters from liquid and gaseous effluent, plutonium-contaminated equipment, fuel transport flasks and reactor components. Some of this waste can be treated to extract and concentrate the long-lived radioactive constituents, discharging the rest as low-level waste. Much of the waste is encapsulated into blocks of concrete, resin or bitumen for longer-term, land-based storage and eventual disposal. Storage is usually made deep underground, at about 300 m depth, at suitably safe geological sites.

High-level nuclear waste is the most dangerous because of the high heat generation and the high level of radioactivity. Concrete-lined, stainless-steel water tanks known as cooling ponds are used to store solid waste for up to ten years. After cooling, the fuel and weapons material can be retrieved for reprocessing. A diagram of a cooling pond is given in Fig. 8.9 [22].

High-level liquid waste is cooled for several years and then solidified. In the UK and France the solidified waste is chemically incorporated into glass cylinders encased in steel cans. The radioactive solids fuse with the glass into an opaque glazed ceramic. In the USA the waste is fused with a ceramic by fluid-bed calcination. The waste containment cans are air- or water-cooled in concrete container buildings or bunkers deep underground, in salt formations or mines that prevent the intrusion of water [23].

The treatment, transportation and disposal of nuclear waste, especially high-level waste, is a major challenge to the nuclear industry. There have been two notable incidents involving the escape of radioactive material: at Windscale (now Sellafield), England, in 1972 and at Hanford, Washington, USA, in 1973. No long-term ill-effects seem to have accrued from either incident. The overall safety record of the UK nuclear industry is excellent.

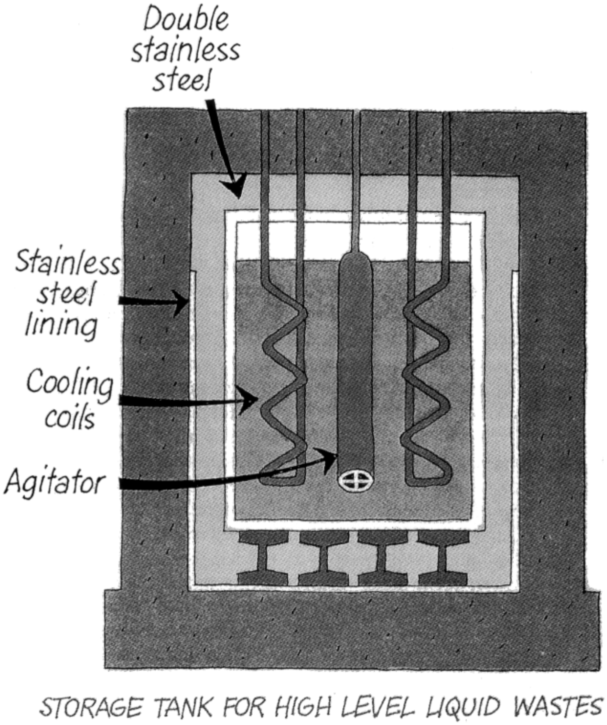


Fig. 8.9. Storage tank for high-level liquid wastes [22] (reproduced by permission of AEA Technology plc).

8.6.3. *Terrorist action*

It would be relatively easy for competent scientists and engineers to make an atomic bomb from a small amount of stolen plutonium. The security of reprocessed fuel in recycling plants or during transportation is vital, as is the management accounting of fissile material in all sections of the nuclear industry.

It is a sad comment on the prevailing politics of the modern world that the threat of terrorism is always present. Great dangers of radioactive release and nuclear explosions exist because of the many countries that now possess fissile materials or nuclear weapons.

8.7. Nuclear-Powered Electricity Generation

It takes about ten years to build a power station in the UK, from the initial design to the commissioning and running stage. Economic assessment always faces the anomaly of present and immediately ongoing building costs versus the returns on electricity sales starting ten years hence. The cost of electricity in ten years' time will depend on a host of engineering, social and political factors which are difficult to forecast accurately. Nevertheless, advance planning has to be undertaken based on assumptions and best estimates of the future, as discussed in Chapter 2. A key issue is the future demand for electricity. Obtaining unbiased economic information with regard to the nuclear power industry is particularly difficult.

A nuclear power station is relatively expensive to build compared with a fossil fuel station, because of the costs of the reactor, fuel handling and elaborate safety features. Some estimates place the building costs of a nuclear plant at twice the level of a coal-fired plant of the same rating. The financial investment is large, pointing to the need for realistic rates of interest on capital costs and on the need to avoid overrunning the construction schedules.

On the other hand, the costs of nuclear fuels are claimed to be lower than equivalent fossil fuels. With cheaper running costs, high load factors in the nuclear-generating stations and a continuing demand for electrical power, it can be seen that, overall, the cost of nuclear power could be cheaper than that of conventional fossil fuel generation.

The world consumption of nuclear fuels for the period 1990–2000 is given in Table 8.5 [15]. It can be seen that the chief users are the USA, France, Japan and Germany. World consumption increases continually due to heavy use in North America and Western Europe, illustrated in Fig. 8.6. The global demand for nuclear-generated electricity rose by a further 2.7% in 2000.

8.7.1. *Nuclear generation in the USA*

The USA is expected to reduce its nuclear reliance from 20% of total electricity generation in 1999 to less than 12% in 2020. However, reductions in operating costs over the past decade have made the nuclear plants more competitive in the increasingly deregulated electricity market.

Since 1997, a wave of consolidation has occurred in the US commercial nuclear power industry through various mergers and acquisitions. The first merger occurred when the PECO Energy Company and British Energy formed a joint partnership, AmerGen, for the express purpose of buying nuclear power plants. AmerGen has purchased five nuclear power plants to date and has plans to purchase as many as 20 plants in total. AmerGen was involved in the first purchase of a US nuclear plant in its entirety in December 1999, when it bought the Clinton plant.

AmerGen and a handful of other companies are emerging as major holders of US nuclear assets. Entergy, for example, has announced plans to spend $1.7 billion over five years to build a portfolio of 12–15 nuclear power units, and Duke Energy, Constellation Energy Group and Northern States Power have also indicated interest in acquiring nuclear units. In addition, PECO and Entergy are involved in two of the largest mergers in the history of the US nuclear power industry. Unicom and PECO completed a merger in October 2000 that created the nation's largest nuclear utility. The combined company, Exelon, owns 17% of the total nuclear generation capacity, with annual revenues of $12 billion.

In another early sale, AmerGen purchased the Clinton nuclear plant for $200 million, even though it cost Illinois Power $4.25 billion to build it. In the Clinton sale, AmerGen assumed full responsibility for the decommissioning. Illinois Power ceded $98 million in decommissioning funds to AmerGen and is committed to transferring additional funds sufficient to fully fund the eventual decommissioning of the Clinton reactor.

More recently, however, prices for nuclear power assets have risen markedly. For instance, in February 2000, Entergy agreed to pay the New York Power Authority $967 million for Indian Point 3 and Fitzpatrick, a record high for nuclear sales to that date. The higher prices paid for nuclear assets in recent sales may reflect not only the quality of the assets sold but also an improved environment for nuclear power in the USA [12].

8.7.2. *Nuclear generation in the UK* [24]

In 1995, the UK government announced that it would privatise its more modern nuclear stations while retaining the ownership of older stations. In 1996, more modern stations were privatised and British Energy became the holding company of Nuclear Electric and Scottish Nuclear, which merged in 1998 to form British Energy Generation, the nation's largest private nuclear generator and the world's first wholly privatised nuclear utility. British Energy operates eight power stations in the UK (as well as several in the USA through its AmerGen subsidiary, which is jointly owned with PECO). Each station consists of two advanced gas-cooled reactors, except Sizewell B, which is a modern pressurised water reactor. Nuclear power stations were not privatised simultaneously with non-nuclear stations. No new plants have been built since 1995. But because of limited domestic coal and gas reserves, new construction is under discussion, at least to maintain nuclear's market share as older nuclear plants are retired. Of the UK's 33 reactors, 26 are of the old Magnox design. Six of the Magnox reactors are being decommissioned, as well as the Dounreay prototype fast reactor. The remaining Magnox plants are run by the state-owned British Nuclear Fuels. British Nuclear Fuels operates the Sellafield reprocessing plant and is one of only two companies in the world that provide reprocessing and recycling technologies. The British nuclear industry is regulated by the Department of Trade and Industry Nuclear Directorate.

8.8. Nuclear Fusion

8.8.1. *Basic theory* [6, 23, 25]

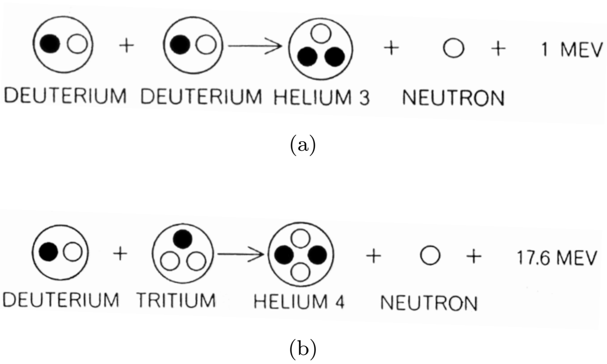
Nuclear fusion is the term describing the union or fusion of two or more light atomic nuclei. If the positive electrostatic repulsive forces of two nuclei can be overcome, to permit fusion, large amounts of energy are released. Many different nuclear fusion reactions occur in the sun and other stars but only a few such reactions are of practical value for potential energy production on earth. These all involve isotopes of the element hydrogen. Three isotopes of hydrogen are known: hydrogen (H), deuterium (D) and tritium (T). The nuclei of all three isotopes contain one proton, which characterises them as forms of the element hydrogen. In addition, the deuterium nucleus has one neutron and the tritium nucleus has two neutrons. In each case, the neutral atom has one electron outside the nucleus to balance the charge of the single proton.

Several different nuclear fusion reactions can be used to release energy for large-scale electricity generation. All of these have in common that the fusions require high energies obtained via very high working temperatures. At a temperature of 40 million kelvins (4×10^7 K) the electrons separate from their associated nuclei. The resultant ionised gas is known as a plasma, in which individual nuclear particles each have an average energy greater than 5 keV. High temperature plasmas conduct electricity and can be confined and controlled by electric and magnetic forces.

Deuterium (D) or heavy hydrogen occurs naturally in seawater and has the mass number 2, as discussed in Sec. 8.1. In a thermonuclear bomb two deuterons fuse to form helium 3 plus a neutron, Fig. 8.10(a). For the purpose of electricity generation by nuclear fusion, the most promising reaction is the deuterium–tritium reaction, illustrated in Fig. 8.10(b) [6].

Tritium (T) is a radioactive isotope of hydrogen, with the mass number 3 and half-life $T_{\frac{1}{2}} = 12.6$ years. It does not occur in nature and has to be manufactured from the natural chemical lithium (Li), which is a plentiful alkali metal that is widely available commercially. The deuterium–tritium (D–T) reaction, Fig. 8.10(b) and equation (8.12), produces the inert gas helium plus energy and further neutrons to sustain the reaction.

$$^{2}\mathrm{D} + {}^{3}\mathrm{T} \rightarrow {}^{4}\mathrm{He} + {}^{1}\mathrm{n} + 17.6\ \mathrm{MeV} \tag{8.12}$$



(a)

(b)

Fig. 8.10. Nuclear fusion reactions [6]: (a) thermonuclear weapon, (b) basis of nuclear fusion electricity generation.

The energetic helium 4 in the D–T reaction, (8.12), is also called an α particle, discussed in Sec. 8.4. In this reaction the α particle carries 20% of the released energy and the remaining 80% (14 MeV) is carried by the neutron. This neutron energy is converted to heat by slowing down the neutrons in a blanket containing lithium surrounding the plasma, Fig. 8.11, which is then transferred to a steam boiler [25]. The neutrons themselves ultimately enter into reactions with lithium to generate tritium which is separated and fed back into the reactor as a fuel.

$$^{1}\mathrm{n} + {}^{6}\mathrm{Li} \rightarrow {}^{4}\mathrm{He} + {}^{3}\mathrm{T} + 4.8\ \mathrm{MeV} \tag{8.13}$$

In effect the tritium produced in (8.13) is recycled in (8.12) to produce a resultant reaction.

$$^{2}\mathrm{D} + {}^{6}\mathrm{Li} \rightarrow 2{}^{4}\mathrm{He} + 22.4\ \mathrm{MeV} \tag{8.14}$$

Equation (8.14) shows that deuterium and lithium are the basic fuels for nuclear fusion. They are both naturally occurring, abundant and stable (i.e. non-radioactive). There are radiation effects, however, because the intermediate tritium reaction and the high energy neutrons released by fusion make the reactor structure radioactive. The quantity of active material in a fusion reactor would be up to 100 times less than in an equivalent fission reactor. Moreover, the intermediate fuel, tritium, has a half-life of 12.6 years, compared with billions of years for uranium and 24,400 years for plutonium [8]. Other forms of fusion reactions are possible but these require temperatures even higher than that of the D–T reaction, which is the most viable.

Deuterium constitutes 1/7000 of the hydrogen in seawater. Complete fusion of the deuterium in 1 cubic metre of seawater would yield 12×10^{12} joules of energy, which is equivalent to about 2000 barrels of oil. Rather more startling is the fact that each cubic kilometre of ocean contains enough deuterium that, if fully converted to heat by nuclear fusion, would be roughly energy equivalent to the earth's known

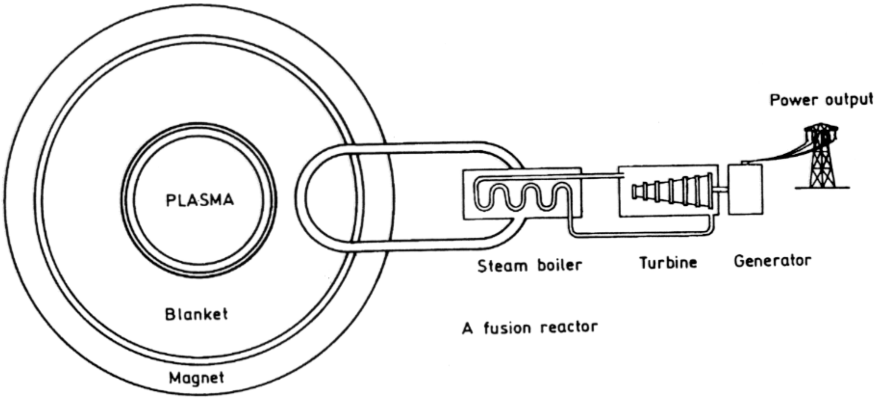


Fig. 8.11. Nuclear fusion heat production [25] (reproduced by permission of UKAEA).

oil reserves. Also, compared with the cost of coal, natural gas or oil, deuterium is virtually free.

Lithium is abundantly available from secure land-based sources. Since the mid-90s, Chile has become the largest lithium chemical producer in the world; Australia, China, Russia and the USA were large producers also. Australia, Canada and Zimbabwe were major producers of lithium ore concentrates. The USA remained the leading consumer of lithium minerals and compounds and the leading producer of value-added lithium materials. Because only one company produced lithium compounds from domestic resources, reported production and value of production data cannot be published. An estimation of value for the lithium mineral compounds produced in the USA is extremely difficult because of the many compounds used in a wide variety of end uses and the great variability of the prices for the different compounds [26]. Some details of the production and reserves of lithium are given in Table 8.6 [26].

Identified world reserves of 13 million tonnes exist against the present consumption of 13,000 tonnes per year for industrial lubricants and ceramics. Immense reserves of lithium also exist in the oceans but would cost much more to extract.

The two basic fuel ingredients of nuclear fusion, deuterium and lithium, are therefore abundant, cheap and non-radioactive. For this reason nuclear fusion is

Table 8.6. World mine production, reserves, and reserve base of lithium [26].

	Mine production		**Reserves**[2]	**Reserve base**[2]
	1999	**2000**[0]		
United States	W	W	38,000	410,000
Argentina[0]	200	200	NA	NA
Australia[0]	2,200	2,000	150,000	160,000
Bolivia	—	—	—	5,400,000
Brazil	32	30	910	NA
Canada	710	710	180,000	360,000
Chile	5,300	5,500	3,000,000	3,000,000
China	2,300	2,000	NA	NA
Portugal	140	140	NA	NA
Russia[0]	2,000	1,800	NA	NA
Zimbabwe	700	700	23,000	27,000
World total (may be rounded)	[3]14,000	[3]13,000	[4]3,400,000	[5]9,400,000

World Resources: The identifed lithium resources total 760,000 tons in the United States and more than 12 million tons in other countries.

[0] Estimated. E Net exporter. NA Not available. W Withheld to avoid disclosing company proprietary data.

[1] Defined as imports − exports + adjustments for Government and industry stock changes.

[2] See Appendix C for definitions.

[3] Excludes US production.

[4] Excludes Argentina, China, Namibia, Portugal and Russia.

[5] Excludes Argentina, Brazil, China, Namibia, Portugal and Russia.

rightly seen as one of the four main hopes to secure the long-term energy future of the world, as discussed in Chapter 14.

8.8.2. *Nuclear fusion reactors*

In order to generate electricity from nuclear fusion, three scientific and engineering challenges have to be overcome [25]:

(a) to create and heat a plasma to temperatures in excess of 10^8 K,
(b) to hold enough plasma away from the container walls for long enough to permit abundant reactions to occur,
(c) to design a practical, safe and economic fusion reactor.

8.8.2.1. *Nuclear plasma properties*

The nuclear fusion of hydrogen into helium takes place naturally in the sun and similar average-sized stars, at interior temperatures of about 2×10^7 °C. To fuse deuterium and tritium into helium, equation (8.12), requires temperatures estimated to be of the order of ten times the sun core temperature, at 100–200 million °C. This has to be maintained for a minimum time period t_m of the order of 1–2 sec.

In the most likely scenario for a fusion power plant, a deuterium–tritium (D–T) mixture is admitted to the evacuated reactor chamber and there ionised and heated to thermonuclear temperatures. The fuel is held away from the chamber walls by magnetic forces long enough for a useful number of reactions to take place. The charged helium nuclei which are formed give up energy of motion by colliding with newly injected cold fuel atoms, which are then ionised and heated, thus sustaining the fusion reaction. The neutrons, having no charge, move in straight lines through the thin walls of the vacuum chamber with little loss of energy.

The neutrons and their 14 MeV of energy are absorbed in a “blanket” containing lithium which surrounds the fusion chamber. The neutrons’ energy of motion is given up through many collisions with lithium nuclei, thus creating heat that is removed by a heat exchanger which conveys it to a conventional steam electric plant [27].

For a continuous steady-state operation the central plasma ion density in nuclei/m^3 must be such as to satisfy a relationship

$$[t_m][\text{nuclei/m}^3] > 2 - 3 \times 10^{20} \tag{8.15}$$

If (8.15) is expressed in terms of atomic nuclei per cubic centimetre,

$$[t_m][\text{nuclei/cm}^3] > 2 - 3 \times 10^{14} \tag{8.16}$$

For a realistic minimum plasma pulse time of 1 sec the necessary density of the D–T gaseous mixture must be of the order 10^{14} atoms/cm^3, which is about one millionth the density of a solid material. At room temperature this ion density corresponds to the low (i.e. high vacuum) pressure of 3×10^{-3} Torr or about 4×10^{-8} pascals.

At the very high working temperatures, of the order 10^8 K, the pressure increases accordingly to the order of 10 atmospheres. The kinetic theory of gases and the gas laws of classical physics do not strictly apply to ionised gases but the ratio of pressure to temperature is fairly constant for a fixed volume of plasma.

8.8.2.2. *Heating of the plasma* [28]

It is seen in (8.14) that each fusion reaction produces 22.4 MeV of heat energy. There must be sufficient fusions per second to sustain the plasma and an excess of reactions, satisfying (8.16), if there is to be net heat energy increase. In the joint European Torus (JET) project, centred in Switzerland, the following methods have been used to heat the plasma.

(a) *Ohmic heating and current drive*

Currents of up to 7 million amperes (7 MA) flow in the plasma and deposit a few megawatts of heating power.

(b) *Neutral beam heating*

Beams of deuterium or tritium ions, accelerated by a potential of 140,000 volts, are injected into the plasma.

In order to penetrate the confining magnetic field, the accelerated beams are neutralised. In the plasma, the beams become ionised and the fast ions give up their energy to the plasma. The maximum power available is 21 MW.

(c) *Radio-frequency heating*

The plasma ions and electrons rotate around in the magnetic field lines of the reactor. Energy is given to the plasma at the precise location where the radio waves resonate within the ion rotation.

Eight antennae in the vacuum vessel propagate waves in the frequency range of 25–55 MHz into the core of the plasma to increase the energy of the ions.

This method can inject up to 20 MW of heating power.

(d) *Current driven by microwaves*

10 MW of microwaves at 3.7 GHz accelerate the plasma electrons to generate a plasma current of up to 3MA. The name of the method, lower hybrid current drive (LHCD), refers to the particular waves excited in the plasma.

(e) *Self-heating of plasma*

The helium nuclei (alpha particles) produced when deuterium and tritium fuse remain within the plasma's magnetic trap. Their energy continues to heat the plasma to keep the fusion reaction going.

When the power from the alpha particles is sufficient to maintain the plasma temperature, the reaction becomes self-heating — a condition referred to as "ignition".

8.8.2.3. *Plasma confinement*

A plasma must be held out of contact with the surface of its containment vessel, to prevent contamination and cooling, for several seconds while the reactions proceed. Cooling due to contact with the container wall would be likely to stop the reactions.

In the sun and other stars, plasma confinement is obtained by gravitational force. This is only effective for immense masses of material and offers no advantage for terrestrial sizes and applications. Two principal methods are the subject of much investigation into fusion research in many countries of the world, namely magnetic confinement and inertial confinement.

Most nuclear fusion research schemes use magnetic field systems to confine the hot plasma. The most common method, which originated in the former Soviet Union, is the toroidal Tokamak scheme, which uses a ring- or doughnut-shaped vacuum chamber, Fig. 8.12 [25]. The plasma current within the ring constitutes the one-turn secondary winding of an electrical transformer. Separation of the plasma from the container walls is obtained by the helical magnetic field which is resultant from two constituent fields. A toroidal field is generated along the major axis by current coils wound around the sectional circumference. Correspondingly, a toroidal field around the minor axis is created by the current in the transformer primary winding, Fig. 8.13 [25]. The net helical field both confines and stabilises the plasma.

Inertial confinement schemes use small pellets, about 1 mm diameter, of deuterium–tritium fuel. These are irradiated by lasers or high-energy electron or ion beams to initiate very fast fusion reactions. The intention is to create a reaction time so fast, of the order one billionth of a second, that the fuel inertia holds it together.

8.8.2.4. *Fusion reactor research*

Scientific research on nuclear fusion has proceeded on a basis of international collaboration since the late 1950s. Plasma physics now represents a major scientific topic in its own right. The USA, Russia, Japan, China and the countries of Western Europe are much involved, especially in Tokamak schemes. In Europe the JET experiment at Culham, Oxfordshire, England, is part of a co-ordinated effort involving Britain, France, Germany, Holland and Italy. The JET system is approximately 15 metres diameter and 12 metres high. A scale model of the vacuum chamber is shown in Fig. 8.14. Experimental evidence suggests the need for still larger devices in order to realise the necessary combinations of plasma density, temperature and confinement times.

A practical fusion reactor scheme of the Tokamak design suitable for safe and reliable electricity provision, rated at (say) 1000 MW_e, is still something like a generation of time away — one is looking to a date about 20–25 years in the future. The design aim must be to create temperatures of the order 10^8 K, for several tens of seconds, within the plasma fusion container. This is a vacuum region with walls thin

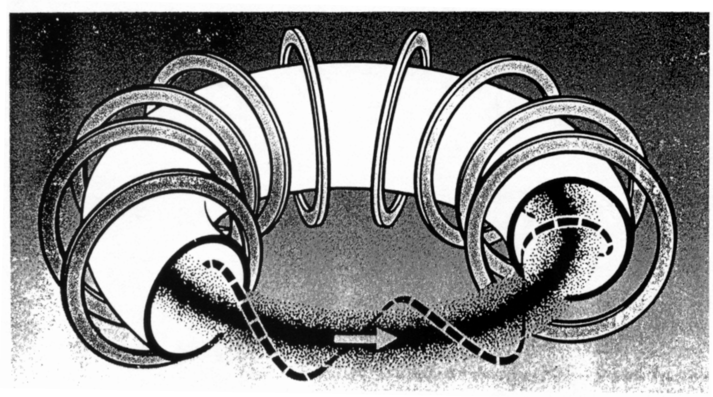


Fig. 8.12. Detail of the Tokamak helical magnetic field [25] (reproduced by permission of UKAEA).

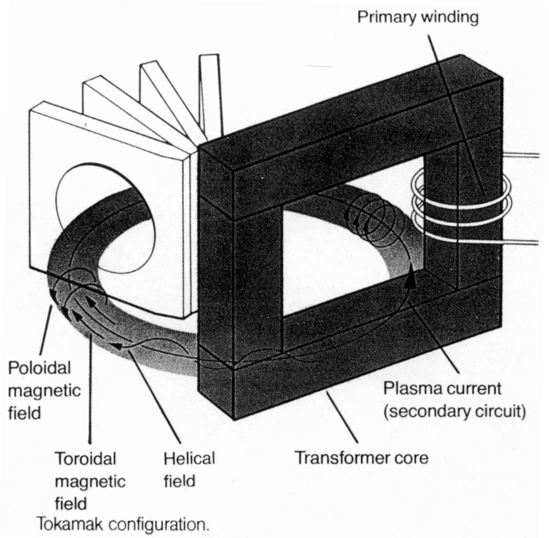

Primary winding
Poloidal magnetic field
Plasma current (secondary circuit)
Toroidal magnetic field
Helical field
Transformer core
Tokamak configuration.

Fig. 8.13. Creation of the toroidal magnetic field [25] (reproduced by permission of UKAEA).

but strong enough to withstand both the high temperatures and the neutron bombardment. The vacuum region must be sheathed in a 1-metre-thick lithium jacket, Fig. 8.11, to slow down high-energy neutrons, breed tritium and carry away heat to exchangers for conversion to steam. Very large magnetic fields, of flux density 10^5 gauss (i.e. 10 webers/m^2 or 10 teslas), require the use of superconducting magnets that operate near to absolute zero temperature. The fusion process creates helium ash that has to be cleared from the reactor but does not create radioactive waste. The development of a working fusion reactor system is many years behind the development of fast breeder fission reactors now operating in France and the UK. This

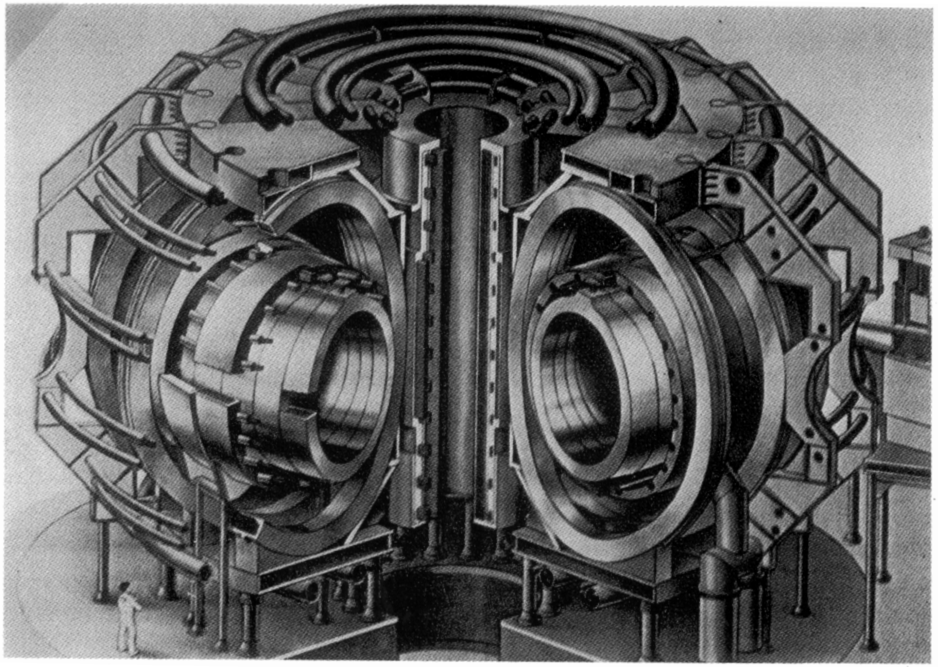


Fig. 8.14. Scale model of the vacuum chamber of the JET fusion experiment [25] (reproduced by permission of UKAEA).

will involve leading edge scientific research and advanced engineering development in several areas concurrently. These include high power superconducting magnets, lasers, vacuum pumping systems, high temperature materials, high neutron flux materials and solution of the basic plasma density-temperature-confinement time problem.

Nuclear fusion offers a safer and more environmentally attractive alternative to nuclear fission:

- The raw materials deuterium (hydrogen) and lithium are abundant, cheap and safe (non-radioactive).
- The process is only slightly radioactive and does not produce nuclear waste.
- The fusion process is intrinsically safe.

Because of the technical complexity of development, it is likely that nuclear-fusion-generated electricity will be more expensive than nuclear fission (thermal) generation. Will nuclear fusion power be sufficiently developed soon enough to fill the energy gap as the fossil fuels run out? Are there better options?

8.9. Problems and Review Questions

8.1. What is the thermal energy equivalent, in tons of coal, to the complete fissioning of 1 kg of uranium 235?

8.2. The fissioning of one atom of U235 has an energy 200 MeV. What is the energy per fission in (i) joules, (ii) kWh?

8.3. Enriched uranium contains 2.3% of U235 in a mixture with U238. Assume that, in a particular fission process, 1% of the U235 is fissioned. What mass of uranium ore has the thermal energy equivalent of 1000 tons of coal? How does this compare with the corresponding calculation for natural uranium?

8.4. How long does it take a radioactive source of half-life $T_{\frac{1}{2}}$ to decay to (i) one tenth, (ii) one hundredth, of its original value N_0?

8.5. List the features of a radioactive source that you would consider to be of interest in studying its properties.

8.6. Uranium 235 has a half-life of 710 million years. How long does it take to decay to one tenth of its original level of activity?

8.7. The radioactive element caesium has a half-life of 30 years. What is the value of its decay constant?

8.8. For cobalt 60 the radioactive decay constant is found to have the value of 0.131. Calculate the half-life.

8.9. How long does it take a radioactive source of half-life $T_{\frac{1}{2}}$ to decay to one thousandth of its original value?

8.10. Define numerical relationships between the following radiation units: rad, rem, millirem, Gray, Sievert.

8.11. What energy is absorbed by a human body in a radiation dose of 100 rads?

8.12. List various forms of natural radiation. What is the average annual dose from natural sources in the UK?

8.13. List various forms of man-made radiation. What is the average annual dose-rate in the UK caused by the nuclear industry? What is the ICRP recommended maximum radiation dose, from all sources?

8.14. Describe, using a diagram, the principle of operation of a nuclear reactor for use in electricity generation. In particular, describe the functions of the core moderator, control gear and coolant.

8.15. In Great Britain and in the USA the use of nuclear energy for electricity generation has stalled. Why is this so?

8.16. The continued long-term use of nuclear fission energy for electricity generation will require the use of fast breeder reactors or plutonium reactors. Why is this so?

8.17. In the UK the fossil-fuel part (i.e. about 90%) of the electricity generation industry has smoothly passed from public to private (public limited company) ownership. There still remains difficulty about privatisation of the nuclear generation industry. Why is this so?

8.18. Describe the three main classes of nuclear waste and how these are treated or disposed of.

8.19. Discuss the difference between nuclear fission and nuclear fusion.

8.20. Explain why the deuterium–lithium nuclear fusion process takes place via an intermediate reaction involving tritium.

8.21. Each nuclear fusion of deuterium and lithium releases 22.4 MeV of thermal energy. What is the equivalent energy in (i) joules, (ii) kilowatt hours?

8.22. Explain why, from the point of view of fuel supply, nuclear fusion represents such a highly appealing option.

8.23. The fission of 1 atom of uranium is equivalent to an energy of 200 MeV whereas the fusion of deuterium and lithium releases 22.4 MeV. Does this mean that nuclear fission is $200/22.4 \approx 9$ times better than fusion?

8.24. List the advantages and disadvantages of nuclear fusion as a means of generating electricity. Is it possible to equate the merits of the scientific, social, economic and environmental factors?

8.25. What are the major technical challenges involved in the development of nuclear fusion reactors for electricity generation?

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CHAPTER 9

WATER ENERGY

The use of a moving stream of water as a source of energy has been known for several thousand years. Early water turbines were used for irrigation purposes. In Europe and in North America water mills have been used for hundreds of years as sources of motive power for the grinding or milling of grain. The principle, illustrated in Fig. 9.1, is that a stream of moving water impinges on the blades or vanes of a horizontal axis water-wheel. Energy is transferred from the moving water to the wheel, which can then be used as a source of slow speed mechanical energy. Many different designs and topologies have been investigated to determine the optimum form of water-wheel configuration. Many different techniques have been used to control the amount and velocity of the moving water so as to maximise the energy collection process. Some of these are discussed below.

9.1. Hydroelectric Power Generation

The chief modern use of water power internationally is as a source of prime power for the generation of electricity. Figure 9.2 illustrates the principle of water falling

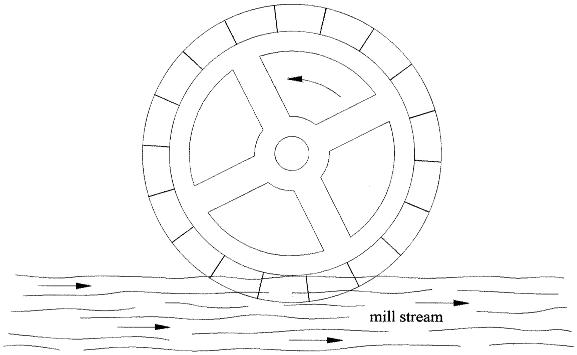


Fig. 9.1. Principle of the water mill.

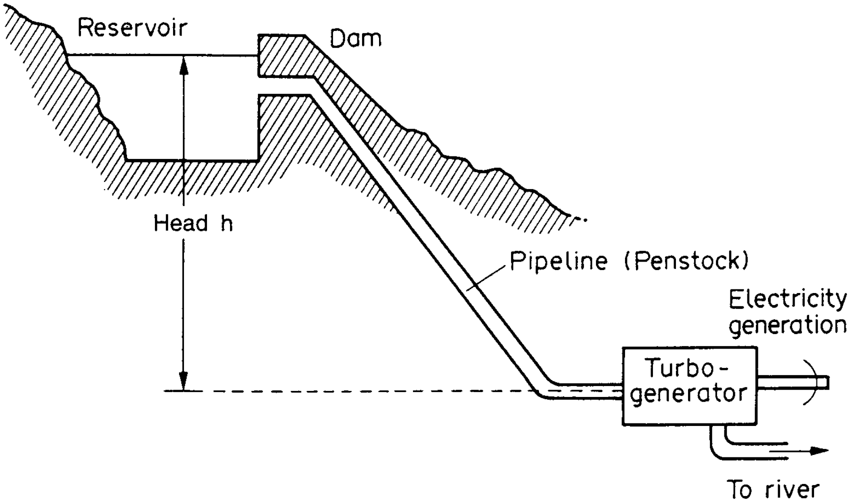

Reservoir
Dam
Head h
Pipeline (Penstock)
Electricity generation
Turbo-generator
To river

Fig. 9.2. Principle of hydroelectric power generation [1].

Fig. 9.3. The Shasta Dam, California, USA [2].

from a high reservoir onto the blades of a water turbine which directly rotates the shaft of an electricity generator. The earliest example of hydroelectric generation in England was in 1880. This was a private plant rated at 5 kW which lighted a picture gallery 1.5 km away. In 1881 electricity was generated from the River Wey in Surrey, England, and used for street lighting in the town of Godalming. Concurrently, in 1882, a hydroelectric station rated at 25 kW began operation on the Fox River in Appleton, Wisconsin, USA, feeding two paper mills plus residential lighting.

The world's first large-scale hydroelectric power station was built at Niagara Falls, New York, USA, in 1895 with a total capacity of 8200 kW. Canada had a 9.3 MW plant in operation at Niagara Falls in 1903 [1]. The vast scale of large modern plants is illustrated in Fig. 9.3, which shows the Shasta Dam in California, USA. This has a spillway three times higher than Niagara Falls and holds 4.5 million acre-feet of water in the the reservoir [2].

About a quarter of the world supply of electricity now comes from hydropower. Developing countries such as Brazil, Ghana, Mozambique, Zaire and Zambia obtained over 85% of their electricity from hydropower in the early 1980s. The Scandinavian countries and Canada generate much of their electricity from hydropower. In Canada the various provincial electricity supply organisations are called Hydroelectric Power Companies. For example, the Canadian province of Quebec is served by the giant electricity company known colloquially as "Quebec Hydro". The USA obtains about 13% of its electricity from hydroelectric stations. There is a small amount of natural hydropower in Scotland but virtually none in England. The largest hydroelectric power plant in the world is located at Churchill Falls, Labrador, Canada, and produces more than 5000 $\mathrm{MW_e}$ of electric power. Hydropower is doubling in capacity, throughout the world, about every 20 years. The potential for further increased development is enormous, especially in the developing countries.

The consumption of hydroelectricity in various countries of the world in the 11-year period 1990–2000 is given in Table 9.1 [3]. Canada is consistently the country with the biggest hydro consumption, although it is increasing in all areas of the world, especially in China, as shown in Fig. 9.4. In 1995 hydroelectric sources contributed 218.5/8135.8 or about 2.7% of the world primary energy consumption.

Hydroelectric projects can be enormous in their scale and size. For example, the Hoover Dam on the Colorado River, USA, is 726 feet high, 660 feet thick at the bottom and 45 feet thick at the top. Lake Mead, contained by the dam, is 110 miles long and holds 26×10^6 acre-feet (315×10^{12} tons) of water. A total of 17 generators have a plant capacity of 1345 $\mathrm{MW_e}$.

To a visitor accustomed to thermal or to fossil-fuel-burning power stations, a hydroelectric generation power plant looks strange — it has no factory chimneys and no strangely shaped cooling towers billowing steam into the atmosphere.

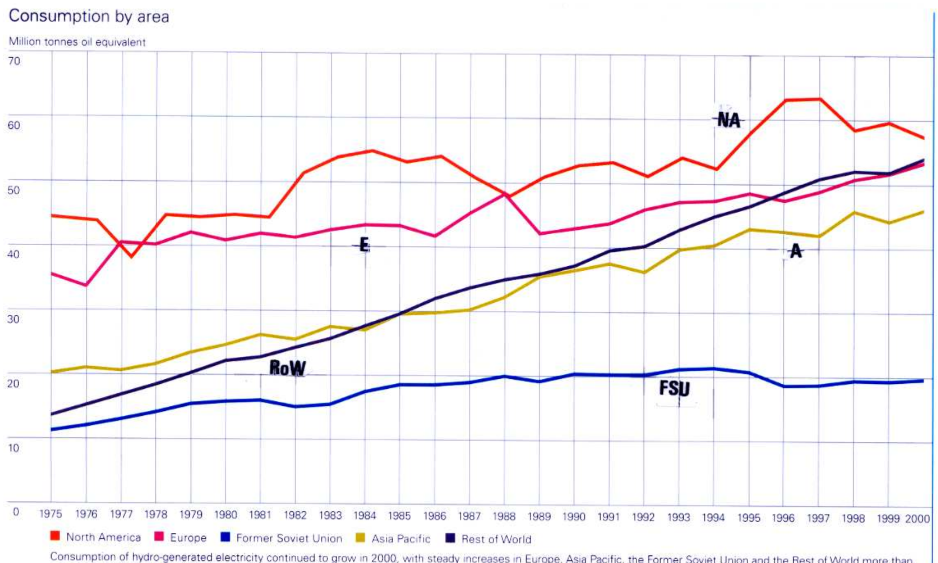
The construction costs of building a hydroelectric plant are larger than the costs of a thermal plant of the same rating. This is because of civil engineering costs such as clearing the reservoir site, building the dam, relocating any buildings or farms

Table 9.1. Hydroelectricity consumption, 1990–2000 [3].

Consumption*

Million tonnes oil equivalent	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	**2000**	Change 2000 over 1999	2000 share of total
USA	25.2	24.8	21.6	24.0	22.3	26.8	29.9	30.8	27.7	27.2	**23.4**	−14.1%	10.1%
Canada	25.5	26.5	27.2	27.7	28.2	28.8	30.5	30.2	28.5	29.6	**30.8**	4.3%	13.4%
Mexico	2.0	1.9	2.3	2.3	1.7	2.4	2.7	2.3	2.1	2.8	**3.2**	15.4%	1.4%
Total North America	52.7	53.2	51.1	54.0	52.2	58.0	63.1	63.3	58.3	59.6	**57.4**	−3.6%	24.9%
Argentina	1.6	1.4	1.7	2.1	2.3	2.3	2.0	2.4	2.3	1.9	**2.0**	5.0%	0.9%
Brazil	17.8	18.7	19.2	20.2	20.9	21.8	22.9	24.0	25.1	25.2	**26.2**	4.1%	11.4%
Chile	0.8	1.1	1.4	1.5	1.5	1.6	1.4	1.6	1.4	1.2	**1.6**	40.7%	0.7%
Colombia	2.4	2.4	1.9	2.4	2.8	2.8	3.1	2.7	2.6	2.9	**2.6**	−8.4%	1.1%
Ecuador	0.4	0.4	0.4	0.5	0.6	0.5	0.5	0.6	0.6	0.6	**0.7**	10.7%	0.3%
Peru	0.9	1.0	0.8	1.0	1.1	1.1	1.1	1.1	1.2	1.2	**1.3**	5.3%	0.5%
Venezuela	3.2	3.8	4.1	4.1	4.4	4.4	4.6	4.9	5.0	5.2	**5.5**	5.5%	2.4%
Other S. & Cent. America	4.3	4.4	4.3	4.9	5.2	5.5	6.3	6.6	6.7	6.7	**6.8**	0.9%	2.9%
Total S. & Cent. America	31.4	33.2	33.8	36.7	38.8	40.0	41.9	43.9	44.9	44.9	**46.7**	4.1%	20.2%
Austria	2.8	2.8	3.1	3.3	3.2	3.3	3.1	3.2	3.3	3.6	**3.7**	1.8%	1.6%
Belgium & Luxembourg	0.1	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.2	0.2	**0.2**	13.1%	0.1%
Bulgaria	0.2	0.2	0.2	0.2	0.1	0.2	0.3	0.3	0.2	0.2	**0.3**	0.4%	0.1%
Czech Republic	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	**0.2**	4.7%	0.1%
Denmark	†	†	†	†	†	†	†	†	†	†	**†**	–	†
Finland	0.9	1.1	1.3	1.2	1.0	1.1	1.0	1.0	1.3	1.1	**1.3**	15.1%	0.5%
France	4.9	5.3	6.2	5.8	7.0	6.5	6.0	5.8	5.7	6.6	**6.2**	−6.1%	2.7%
Germany	1.7	1.6	1.8	1.8	1.9	2.1	1.9	1.8	1.8	2.0	**2.1**	5.0%	0.9%
Greece	0.2	0.3	0.2	0.2	0.2	0.3	0.4	0.4	0.3	0.4	**0.3**	−18.7%	0.1%
Hungary	†	†	†	†	†	†	†	†	†	†	**†**	–	†
Iceland	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	**0.5**	5.0%	0.2%
Republic of Ireland	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	**0.1**	1.1%	†
Italy	3.0	3.9	3.9	3.8	4.1	3.6	4.0	4.0	4.1	3.9	**3.8**	−1.6%	1.7%
Netherlands	†	†	†	†	†	†	†	†	†	†	**†**	25.0%	†
Norway	10.4	9.5	10.1	10.3	9.7	10.5	8.9	9.5	10.0	10.5	**12.2**	16.7%	5.3%
Poland	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	**0.4**	−4.1%	0.2%
Portugal	0.8	0.8	0.4	0.8	0.9	0.7	1.3	1.1	1.1	1.1	**1.1**	−0.9%	0.5%
Romania	0.9	1.2	1.0	1.1	1.1	1.4	1.4	1.5	1.6	1.6	**1.3**	−19.3%	0.6%
Slovakia	0.2	0.2	0.2	0.3	0.4	0.4	0.4	0.4	0.4	0.4	**0.4**	−2.2%	0.2%
Spain	2.3	2.4	1.8	2.2	2.5	2.1	3.6	3.2	3.4	2.6	**3.1**	15.8%	1.3%
Sweden	6.3	5.5	6.4	6.5	5.1	5.8	4.4	5.9	6.3	6.2	**6.8**	9.7%	2.9%
Switzerland	2.7	2.9	2.9	3.1	3.4	3.1	2.6	3.0	3.0	3.5	**3.3**	−6.8%	1.4%
Turkey	2.0	2.0	2.3	2.9	2.6	3.1	3.5	3.4	3.6	3.0	**2.7**	−10.9%	1.2%
United Kingdom	0.6	0.5	0.6	0.5	0.6	0.6	0.4	0.5	0.6	0.7	**0.7**	2.8%	0.3%
Other Europe	1.9	2.5	2.2	2.0	2.2	2.4	3.1	2.5	2.6	2.7	**2.7**	−2.9%	1.2%
Total Europe	42.8	43.8	45.7	47.0	47.2	48.4	47.5	48.7	50.7	51.5	**53.4**	3.2%	23.1%
Azerbaijan	0.1	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.2	0.1	**0.1**	1.5%	0.1%
Belarus	†	†	†	†	†	†	†	†	†	†	**†**	–	†
Kazakhstan	0.6	0.6	0.6	0.7	0.8	0.7	0.6	0.6	0.5	0.6	**0.6**	–	0.3%
Lithuania	†	†	†	†	0.1	0.1	0.1	0.1	0.1	0.1	**0.1**	−28.4%	†
Russian Federation	14.3	14.5	14.8	15.1	15.1	15.2	13.2	13.5	13.6	13.8	**14.2**	2.7%	6.2%
Turkmenistan	0.1	0.1	0.1	–	–	–	–	–	–	–	**–**	–	–
Ukraine	0.9	1.0	0.7	1.0	1.1	0.9	0.8	0.9	1.4	1.0	**0.9**	−6.0%	0.4%
Uzbekistan	0.6	0.5	0.5	0.6	0.6	0.5	0.6	0.5	0.5	0.6	**0.6**	–	0.2%
Other Former Soviet Union	3.6	3.3	3.3	3.5	3.5	3.2	3.2	3.0	3.1	3.1	**3.1**	0.5%	1.4%
Total Former Soviet Union	20.2	20.2	20.2	21.1	21.4	20.7	18.6	18.7	19.4	19.3	**19.6**	1.6%	8.6%
Iran	0.6	0.6	0.8	0.8	0.7	0.7	0.7	0.5	0.6	0.4	**0.4**	−3.8%	0.2%
Kuwait	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Qatar	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Saudi Arabia	–	–	–	–	–	–	–	–	–	–	**–**	–	–
United Arab Emirates	–	–	–	–	–	–	–	–	–	–	**–**	–	–
Other Middle East	0.2	0.2	0.3	0.2	0.3	0.4	0.4	0.4	0.4	0.3	**0.3**	22.8%	0.1%
Total Middle East	0.8	0.8	1.1	1.0	1.0	1.1	1.1	0.9	1.0	0.7	**0.7**	6.2%	0.3%
Algeria	†	0.1	0.1	0.1	†	0.1	†	†	0.1	†	**†**	−70.6%	†
Egypt	0.8	0.9	0.9	0.9	1.0	1.0	1.0	1.0	1.1	1.1	**1.1**	3.2%	0.5%
South Africa	0.2	0.3	0.2	0.1	0.2	0.2	0.3	0.4	0.3	0.3	**0.3**	18.8%	0.2%
Other Africa	4.0	4.2	4.1	3.9	4.0	4.2	4.3	4.4	4.6	4.9	**5.1**	5.2%	2.2%
Total Africa	5.0	5.5	5.3	5.0	5.2	5.5	5.6	5.8	6.1	6.3	**6.5**	5.3%	2.9%
Australia	1.3	1.4	1.3	1.5	1.4	1.3	1.4	1.3	1.4	1.5	**1.4**	−5.9%	0.6%
Bangladesh	0.1	0.1	0.1	0.1	0.1	†	0.1	0.1	0.1	0.1	**0.1**	4.2%	†
China	10.9	10.8	11.4	12.4	14.3	16.0	16.1	16.1	17.1	16.8	**19.0**	13.4%	8.3%
China Hong Kong SAR	–	–	–	–	–	–	–	–	–	–	**–**	–	–
India	5.7	6.4	6.0	6.1	6.9	6.5	5.9	6.0	7.2	7.1	**6.6**	−6.4%	2.9%
Indonesia	0.5	0.5	0.7	0.7	0.6	0.6	0.7	0.4	0.8	0.8	**0.8**	6.7%	0.4%
Japan	8.1	8.9	7.6	9.0	6.6	7.6	7.5	8.1	9.0	8.0	**7.9**	−1.3%	3.4%
Malaysia	0.3	0.4	0.4	0.4	0.6	0.5	0.4	0.3	0.3	0.4	**0.4**	2.8%	0.2%
New Zealand	2.0	1.9	1.8	2.0	2.2	2.3	2.2	2.0	2.1	2.0	**2.1**	3.6%	0.9%
Pakistan	1.5	1.6	1.7	1.9	1.9	2.0	2.1	1.6	2.1	1.8	**1.6**	−15.8%	0.7%
Philippines	0.5	0.4	0.4	0.4	0.5	0.5	0.6	0.5	0.4	0.7	**0.7**	−3.4%	0.3%
Singapore	–	–	–	–	–	–	–	–	–	–	**–**	–	–
South Korea	0.5	0.4	0.4	0.5	0.4	0.5	0.4	0.5	0.5	0.5	**0.5**	−7.7%	0.2%
Taiwan	0.7	0.5	0.7	0.6	0.8	0.8	0.8	0.8	0.9	0.8	**0.8**	−0.8%	0.3%
Thailand	0.4	0.4	0.4	0.3	0.4	0.6	0.6	0.6	0.4	0.3	**0.5**	70.7%	0.2%
Other Asia Pacific	3.8	3.9	3.3	3.4	3.5	3.7	3.7	3.5	3.4	3.5	**3.7**	5.9%	1.6%
Total Asia Pacific	36.3	37.6	36.2	39.3	40.2	42.9	42.5	41.8	45.7	44.3	**46.1**	4.1%	20.0%
TOTAL WORLD	**189.2**	**194.3**	**193.4**	**204.1**	**206.0**	**216.6**	**220.3**	**223.1**	**226.1**	**226.6**	**230.4**	**1.7%**	**100.0%**
of which: OECD	104.2	105.5	104.3	110.4	106.2	113.7	116.9	119.2	117.2	118.2	**118.0**	−0.2%	51.2%
European Union 15	23.7	24.5	26.0	26.3	26.8	26.4	26.4	27.2	28.2	28.5	**29.4**	2.9%	12.8%
Other EMEs‡	61.6	64.5	65.3	69.0	74.6	77.8	79.6	80.5	84.7	84.2	**88.1**	5.0%	38.2%

*Converted on the basis of the energy content of the electricity generated.
†Less than 0.05.
‡Excludes Central Europe and Former Soviet Union.



Consumption of hydro-generated electricity continued to grow in 2000, with steady increases in Europe, Asia Pacific, the Former Soviet Union and the Rest of World more than offsetting a decline in North America.

Fig. 9.4. Hydroelectricity consumption, 1975–2000, by geographical area [3].
NA = North America E = Europe
FSU = Former Soviet Union
A = Asia-Pacific RoW = Rest of World

that lie within the water basin, lengths of the access roads on the site, etc. Capital investment costs for any hydroelectric scheme in the UK, including pumped-storage and tidal-barrage schemes, are now in the range £200–500 per kilowatt of proposed electrical output power.

On the other hand, the running costs of a hydroelectric plant are the cheapest option available because the fuel is free. Since the tendency is for fossil fuels such as coal, oil and natural gas to increase in price, the likelihood is that hydroelectric schemes will gain an increasing cost advantage.

The potential hydro capacity in various countries is given in Fig. 9.5 [4]. The former Soviet Union and China consumed far less than Canada and the USA in 2000, Table 9.1, but both have enormous hydro potential.

9.1.1. *Principles of hydroelectric plant operation*

The natural hydrological weather cycle consists of evaporation, precipitation and surface run-off. During evaporation water vapour is convected to high altitudes and gains heat energy and gravitational potential energy due to its mass and height. On precipitation this potential energy and heat energy are released. Large masses of moving water are sources of kinetic energy. Large masses of stationary water are sources of stored potential energy.

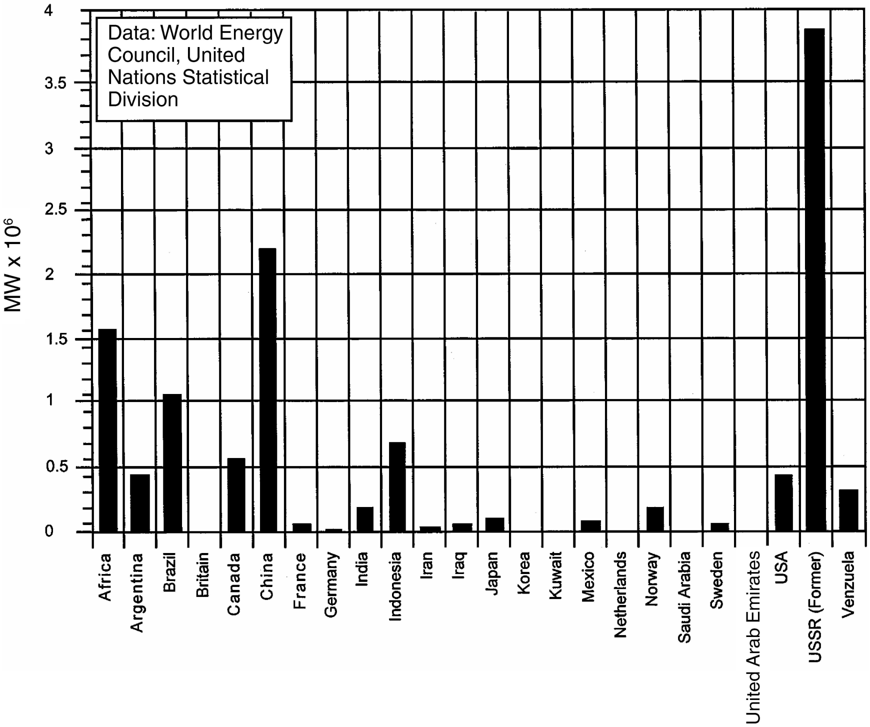


Fig. 9.5. Hydroelectricity potential capacity [4].

In order to ensure an adequate supply of water, most hydroelectric schemes use dams for retaining a reservoir of water. This reservoir is replenished by rainfall from the surrounding countryside so that the depth of water varies with the local climate. Most hydropower water reservoirs are pleasant and attractive places that fulfil recreational and environmental functions, in addition to their primary purpose.

Let the head (e.g. height) of water in the reservoir be h metres, Fig. 9.2. For a mass of water m kilogrammes, the potential energy in watt-seconds or joules is

$$W_P = \text{Gravitational potential energy} = mgh \tag{9.1}$$

where g is the gravitational acceleration in m/s^2. The energy W_P can also be expressed in terms of the volumetric flow rate Q and the density ρ of the water

$$W_P = Q\rho gh \tag{9.2}$$

where Q is in m^3/s.

It is clear from (9.2) that the potential energy of stored water can be released either by using a large volumetric flow rate and a small head height or a small volumetric flow rate falling through a large height.

Now the potential energy lost in falling is equal to the kinetic energy KE gained by the water plus the energy losses incurred.

$$\text{KE} = \text{Kinetic energy} = \frac{1}{2}\, mV^2 \tag{9.3}$$

where V is the velocity of the water impinging on the blades of the turbine. Neglecting the losses and equating (9.1) and (9.3) gives a maximum possible value for the velocity

$$V_{\text{max}} = \sqrt{2gh} \tag{9.4}$$

Some of the energy in the reservoir, or head water, is lost due to friction and turbulence at the inlet and outlet pipes and also in the penstock or downpipe. In many systems the penstock follows the contours of the ground surface, which is of much greater length than the vertical head height. Most of the kinetic energy at the turbine blades is imparted to its shaft, with an efficiency η_t greater than 90%. Energy from the water is thereby converted directly into rotational mechanical energy, without any intervening energy conversion process. Large electricity generators of the size used in hydroelectric systems are also highly efficient with efficiency values η_g of the order 95% or greater. The combination efficiency $\eta_t \eta_g$ between the water power at the turbine blades and the electrical output power is of the order 85%. Because of the various water flow losses, however, the ratio of the electrical output power to the reservoir water power is of the order 75–80%. This overall efficiency η_0 figure is much greater than can be obtained by a wind turbine system or by a heat–work cycle involving a boiler plus a steam engine, a gas or diesel engine, or a nuclear reactor system.

9.1.2. *Types of hydraulic turbine*

9.1.2.1. *Impulse turbines*

In the most common form of water turbine, known as the impulse turbine, a jet or jets of pressurised water are directed against vanes or cups placed on the perimeter of a wheel, Fig. 9.6. The consequent force on the rotor is intermittent and impulsive. Many different configurations of turbine blade have been used, such as those of Fig. 9.7, in which the jet of water is applied tangentially to the turbine rotor.

The most successful of the impulse-type water turbines uses the Pelton wheel, Fig. 9.8 [5]. Water jets are directed against a structure of double hemispherical cups cast on to the turbine rotor. The high-velocity water jets are designed to strike the cups perpendicularly at the speed that will result in the maximum transfer of momentum. Pelton wheel turbines are suitable for systems with large heads of water, 1200 feet and higher. For example, there is a 6-jet, 429 rpm system, rated at 29 MW (39,000 HP), operating with a head of 1233 feet, and developing an

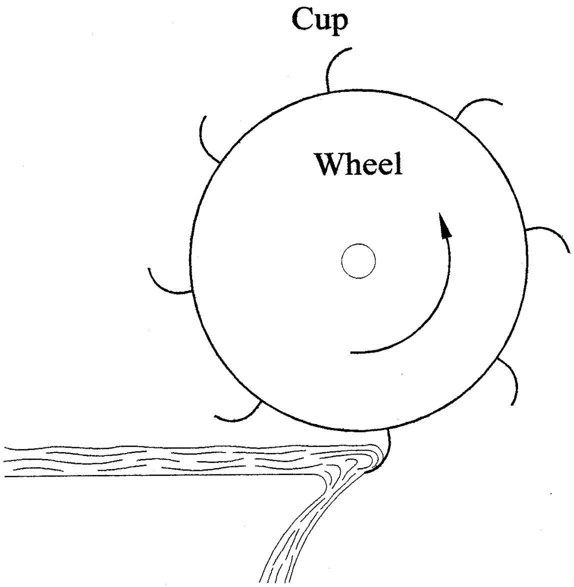
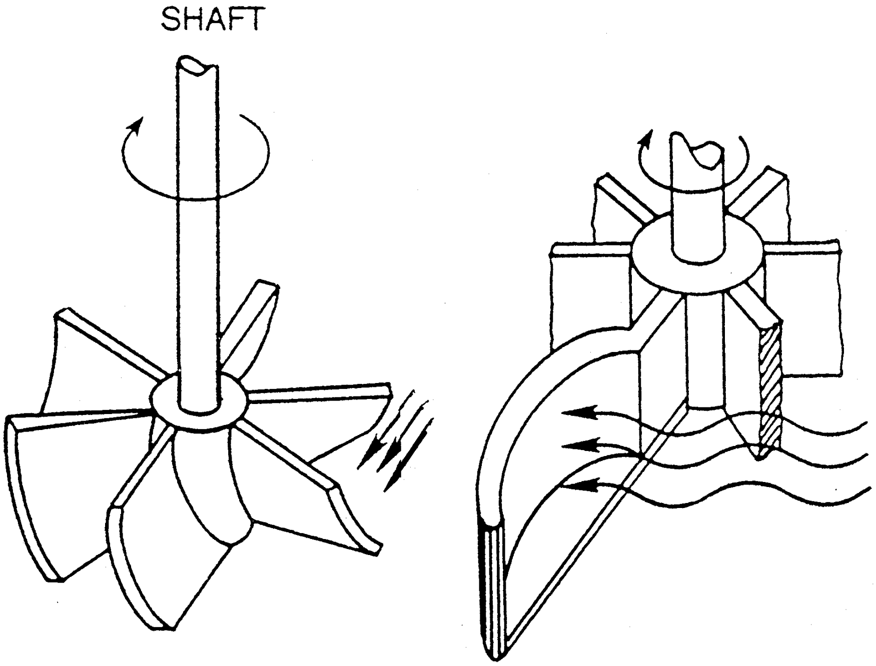


Fig. 9.6. Principle of the impulse turbine.



(a) (b)

Fig. 9.7. Configurations of impulse turbine blades: (a) Greek turbine, (b) Irish turbine [5].

efficiency of 60% at 1/10 rated output. Large commercial installations typically have full-load efficiencies of the order 90%, whereas small installations are of the order 50% [5].

9.1.2.2. *Reaction turbines*

When the head of water available is in the range 5 m $\leq h \leq$ 400 m, a Pelton wheel system would require too many jets. From (9.2) it is seen that the volumetric flow rate of the water at the turbine blades must then be increased considerably. This can be achieved using, for example, the structure illustrated in Fig. 9.9 [5]. The periphery of the turbine rotor is encased in a housing that permits continuous fluid pressure against the blades. The water enters radially but leaves axially, parallel to the shaft. Because the water exerts continuous pressure on the blades, these react continuously, giving rise to the generic name "reaction turbiner". In addition to the kinetic energy extracted from the water flow, a pressure head exists across the turbine, giving also a component of potential energy.

A typical installation of this so-called mixed-flow radial turbine or Francis reaction turbine has a diameter of 19 feet and delivers 104 MW (140,000 HP) at 100 rpm, using a water head of 162 feet.

9.1.2.3. *Axial flow turbines*

When only a relatively small head of water is available, of the order 3 m $\leq h \leq$ 30 m, a large volumetric flow rate is needed in order to develop significant levels of power. This can be realised by the use of an axial flow type of turbine, utilising a propeller [5].

The principle of the axial flow, propeller type of turbine is illustrated in Fig. 9.10 [5]. The inlet water flow is restricted by a nozzle which increases the water pressure by the Venturi effect. Water flows in the axial direction of the propeller. Guide vanes (not shown in Fig. 9.10) impart a whirl or rotary component of force to the blades, resulting in rotation. If the propeller blades are of fixed pitch they have a high conversion efficiency at full load but a poorer performance, typically 50% efficiency, at part load. The use of variable pitch blades, as in the Kaplan turbine, gives high efficiency, typically 90%, at all levels of output but is much more expensive.

9.1.3. ***Pumped storage systems***

The load on electricity generation and distribution systems is spread unevenly throughout a 24-hour day. Usually the peak load demand occurs during the daytime, and the night-time load is much smaller. A feature of this load spread is that some very expensive generation equipment is only lightly loaded or is totally unused during the hours of darkness, which is uneconomical. The economics of electricity generation requires a maximum utilisation of the plant, preferably at its rated

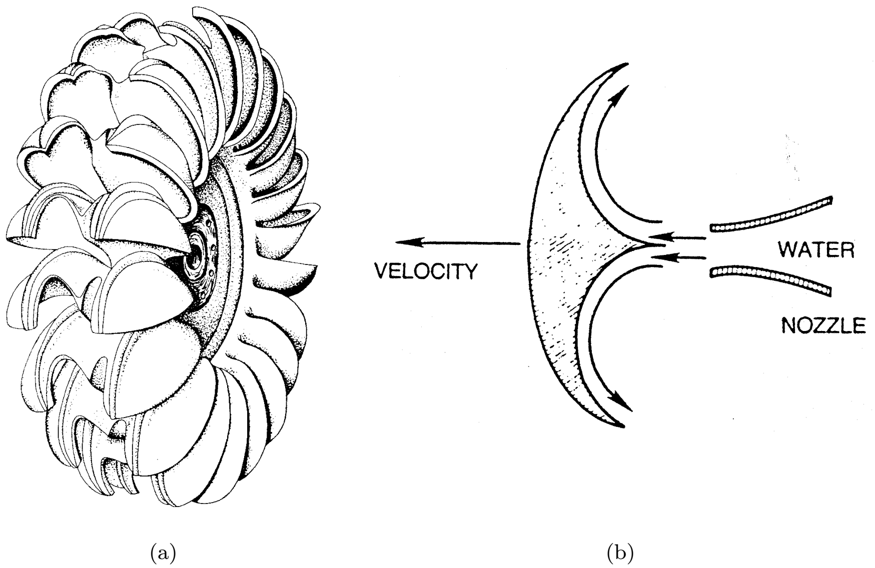


Fig. 9.8. Pelton wheel: (a) turbine runner construction, (b) water deflection action [5].

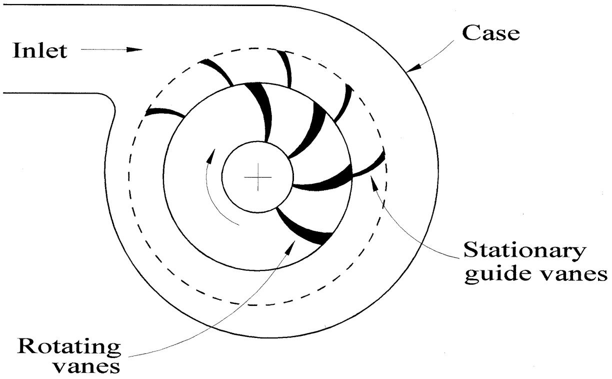


Fig. 9.9. Structure of the reaction (radial flow) Francis turbine [5].

operating levels. Because of the underuse of generation equipment at night-time, it is possible in the UK to buy "off-peak" electricity at reduced tariffs.

A principal use of the night-time spare generation capacity is in pumped storage schemes. Generators that would otherwise be unused are operated to pump water up from turbine level to high storage reservoirs. Electric motors are used to drive the water pumping units, which sometimes comprise the water turbines in reverse. Stored water is then available as a top-up for driving the water turbines during the peak demand hours of daylight, which represents a saving of plant costs. In order to be economical, the energy saving due to pumped storage generation by day has

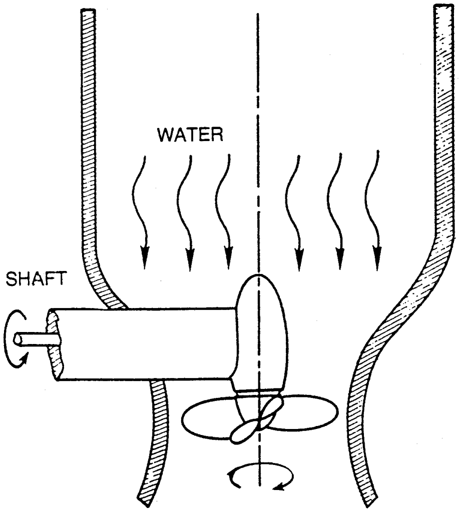


Fig. 9.10. Axial flow (propeller) turbine [5].

to exceed the cost of pumping the water into the reservoir by night, including the amortised costs of the pumped storage installation.

The pump efficiency η_p used to pump water into the storage reservoirs is about 90%. Combining this efficiency factor with the overall efficiency η_0 from Sec. 9.1.1 gives a total efficiency η_{ps} in the presence of pumped storage.

$$\eta_{ps} = \eta_0 \eta_p \tag{9.5}$$

If the overall efficiency η_0 without pumped storage is 80%, then, with pumped storage,

$$\eta_{ps} = 0.8 \times 0.9 = 0.72 \text{ per unit} \tag{9.6}$$

In spite of the significant reduction of plant efficiency with pumped storage schemes, they still represent a great cost saving because they eliminate the need for additional conventional generation plant.

The world's largest pumped storage scheme is at Ludington, Michigan, USA, which takes its water from Lake Michigan and delivers a peak capacity of 1900 MW_e of electrical power from its 2 mile × 1 mile reservoir. In Europe, the largest pumped storage scheme is at Dinorwig in North Wales, where a power station is built inside an excavated mountain. The upper reservoir is at a height of 568 m above the turbines. Six turbo-generator units are each rated at 300 MW_e. Full output can be delivered for 5 hours and the power station can come on-stream within 10 seconds of demand.

9.1.4. *Worked examples on hydroelectric power generation*

Example 9.1

A water reservoir contains a head of water 400 m above the turbine level. The overall efficiency of the penstock, turbine and generator is 80%. It is required to generate 300 MW of electrical power. What is the necessary mass flow rate of water through the turbines?

The necessary input power is

$$P_{\text{in}} = \frac{P_{\text{out}}}{\eta} = \frac{300\ \text{MW}}{0.8} = 375\ \text{MW} = 375 \times 10^6\ \text{J/s}$$

The stored water in the reservoir must contain the potential energy PE to deliver this power.

Now, from (9.1)

$$\text{PE} = mgh$$

The power associated with this PE $= m \times 9.81 \times 400$ J/s when m is the mass flow rate in kg/s.

Therefore

$$m \times 9.81 \times 400 = 375 \times 10^6$$

or

$$m = 95.6 \times 10^3\ \text{kg/s}$$

Since a cubic metre of water weighs 1000 kg, the volumetric flow rate is

$$Q = 95.6\ \text{m}^3/\text{s}$$

Example 9.2

In the pumped storage scheme at Dinorwig, North Wales, the upper reservoir is at a height of 568 m above the turbine house. If losses are neglected, what is the velocity of the water arriving at the turbine blades?

From (9.1) and (9.2)

$$mgh = \frac{1}{2}mV^2$$

Velocity V then has its maximum theoretical value V_{max}

$$V_{\text{max}} = \sqrt{2gh} = \sqrt{2 \times 9.81 \times 568}$$

$$V_{\text{max}} = \sqrt{11144} = 105.6\ \text{m/s}$$

Example 9.3

In a pumped storage scheme of height 400 m, the combined efficiency of the turbine, electric generators and storage pump motors is 70%. If a water volumetric flow of

50 m^3/s strikes each turbine blade, calculate the electrical output power and the water velocity of impact.

A cubic metre of water weighs 1000 kg, so that

$$Q = 50\ \text{m}^3/\text{s} \equiv 50,000\ \text{kg/s mass flow rate}$$

From (9.1) the gravitational potential energy is

$$\text{PE} = mgh$$

When the mass flow rate is given in terms of mass per unit time, the power potential is

$$\begin{aligned}\text{Potential power of the stored water} &= \frac{\text{PE}}{\text{time}} = 50 \times 10^3 \times 9.81 \times 400\\ &= 196.2 \times 10^6\ \text{J/s}\\ &= 196\ \text{MW}\end{aligned}$$

At an efficiency η of 70% the output power from each generator is

$$P_{\text{out}} = \eta \times \text{power potential} = 0.7 \times 196 = 137.2\ \text{MW}$$

From (9.4), the final velocity of the water, neglecting losses, is

$$V = \sqrt{2gh} = \sqrt{2 \times 9.81 \times 400} = \sqrt{7848} = 88.6\ \text{m/s}$$

9.2. Tidal Power Schemes

Tidal energy is the most predictable form of the various renewable energy sources. Not only is the timing predictable but the scale of the event and its potential energy content can be accurately calculated.

Tides are caused by gravitational and kinematic forces due to motions of the earth, the moon and the sun. At any point on the earth's surface, on land or at sea, there is a gravitational effect, depending on the positions and distances of the sun and moon. The moon orbits the earth with a period of approximately 655.7 hours. But the earth itself rotates about its tilted axis every 23 hours, 56 minutes, 4 seconds (to the nearest second). The combined effect of these two motions creates a tidal period of approximately 24.8 hours which contains two complete tidal cycles. When the earth, sun and moon are almost in line, Fig. 9.11, the tidal effect is a maximum and results in what are called "spring tides". When the moon and sun are perpendicular relative to the earth, the tidal effect is a minimum and results in so-called "neap tides". A spring tide can be as great as three or four times the smallest neap tide [6].

The difference in water level between high tide and low tide is known as the tidal range. In the mid-oceans this is less than 1 metre. There are some large areas of

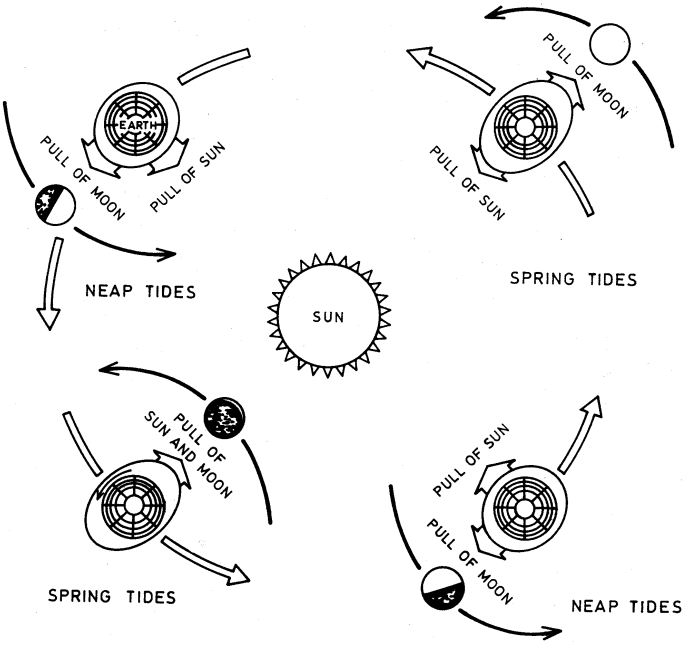


Fig. 9.11. Gravitational basis of ocean tides [6].

water such as the Great Lakes of North America and the Mediterranean Sea where the tidal effect is negligible.

Closer to land, on the continental shelves, the tidal range becomes about 2 metres. Great opportunities for using tidal energy arise in certain river estuaries, bays and basins because the tidal range can be increased to about 16 m by shelving, funnelling and other geographical effects. An incoming tidal wave from the sea may be reinforced by tidal waves reflected from the banks. It is the slow-moving wave nature of tidal water that makes the tides so predictable.

9.2.1. *Tidal power sites*

Hundreds of potentially useful sites for tidal power exploitation exist in different locations across the world. The basic essential prerequisite is an adequate tidal range. Table 9.2 shows some characteristics of the best-known tidal power opportunities [1, 7, 8]. The Rance River project in France, operating successfully since 1966, uses a dam wall 725 m long and delivers an average electrical power of 160 $\mathrm{MW_e}$. The only modern tidal plant in North America is the Annapolis Royal plant in Nova Scotia, Canada. This 20 MW facility uses the outflow tide, which has a head of 7 m, to produce an annual generation of 50 GWh.

The nearby Bay of Fundy, containing the Cumberland Basin and the Minas Basin, could deliver 5000 MW and involve a barrage (dam wall) of length 8000 m

Table 9.2. Major world tidal power sites [1, 7, 8].

	Actual and Potential						
	Mean range (m)	Basin area A (km^2)	Barrage length L (m)	L/A (m/km^2)	Theoretical mean power (MW)	Actual mean power (MW)	Annual production (1000 MWh)
North America							
Passamaquoddy	5.5	262	4270	16.3	1800	378	15,800
Cobscook	5.5	106			722		6330
Annapolis	6.4	83			765		6710
Minas-Cobequid	10.7	777	8000	10.3	19,900	4743	175,000
Amherst point	10.7	10			256		2250
Shepody	9.8	117			520		22,100
Cumberland	10.1	73			1680		14,700
Petitcodiac	10.7	31			794		6960
Memramcook	10.7	23			590		5170
South America							
San Jose, Argentina	5.9	750			5870		51,500
England							
Severn	9.8	70	3500	50	1680	370	14,700
France							
Aber-Benoit	5.2	2.9			18		158
Brest		92	3640	40		211	
Arguenon	8.4	28			446		3910
Frenaye	7.4	12			148		1300
La Rance	8.4	22	725	33	349	160	3060
Rotheneuf	8.0	1.1			16		140
Mont St Michel (Chausey)	8.4	610	23,500	39	9700	5252	85,100
Somme	6.5	49			466		4090
Ireland							
Strangford Lough	3.6	125			350		3070
FSU							
Kislaya	2.4	2	30.5	15.25	2	1.8	22
Lumbouskii Bay	4.2	70			277		2430
White Sea	5.65	2000			14,400		126,000
Mezen Estuary	6.6	140			13,700		12,000
Australia							
Kimberley	6.4	600			630		5600
					∼62,000		∼560,000

outfitted with 97 sluice gates. In the UK interest has been devoted to the River Severn estuary, lying between South Wales and the South West area of England. A sorry tale of missed opportunity has existed since the first favourable UK government report was published in 1933. Further studies and feasibility reports have proposed different schemes and detailed sites. A joint government–industry proposal

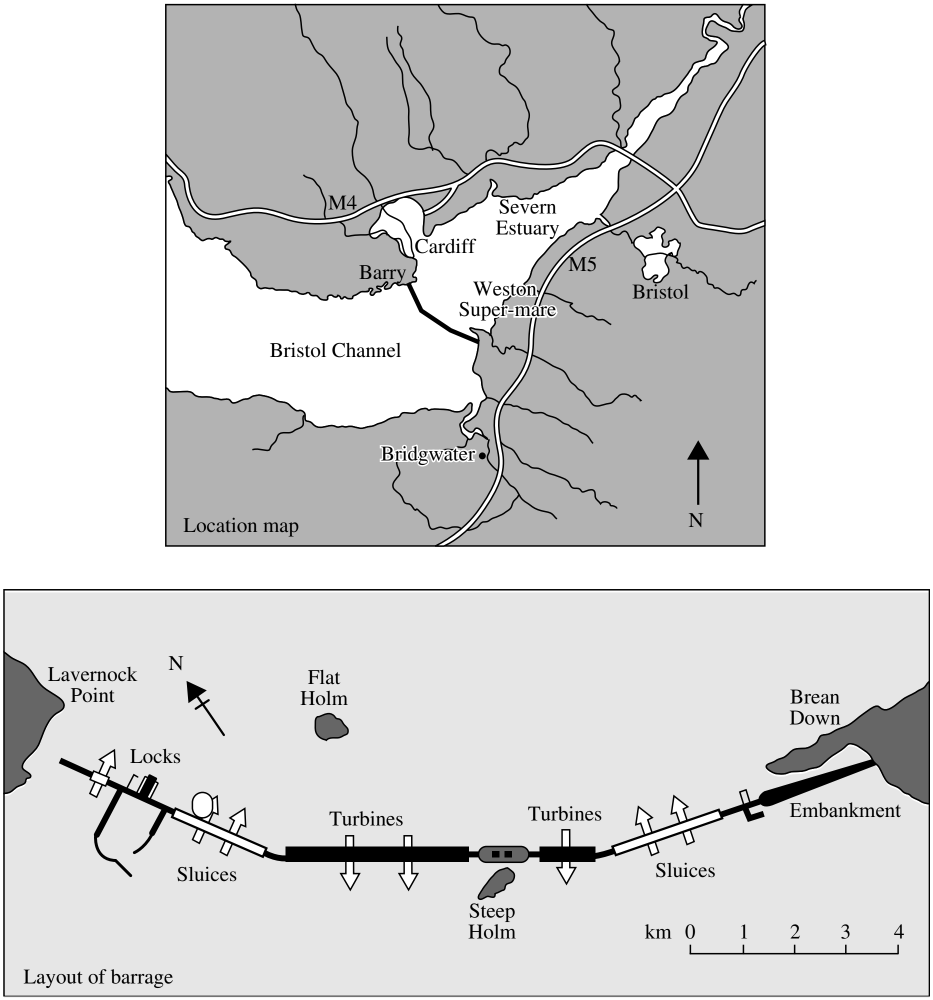

M4
Severn
Estuary
Cardiff
Barry
M5
Weston-
Super-mare
Bristol
Bristol Channel
Bridgwater
N
Location map
Lavernock
Point
N
Flat
Holm
Brean
Down
Locks
Embankment
Turbines
Turbines
Sluices
Sluices
Steep
Holm
km 0 1 2 3 4
Layout of barrage

Fig. 9.12. Possible option for the Severn Barrage.

in 1983 was for a barrage of length 13 km. Some detail of one possible UK option is shown in Fig. 9.12. In 1984 a private consortium suggested an alternative site using a 6.7 km barrage. The enormous cost of a tidal barrage scheme is such that only government sponsorship could support it. At the present period (2002) the cheap price of oil makes it unlikely that any new tidal schemes will proceed anywhere.

9.2.2. *Principles of tidal power operation*

In tidal power schemes the flow of water caused by the tides is harnessed to pass through hydroelectric turbines which drive electric generators. Large water basins are created by the damming or partial damming of rivers or estuaries. The dams are usually referred to as water barrages or, more simply, as barrages. The erection of a water barrage and its attendant turbine houses, sluice gates, navigable channels, etc., is obviously a major civil engineering task. It is possible to use both the inflow (flood) tides and the outflow (ebb) tides for electricity generation, Fig. 9.13 [9]. Two directional turbines are more expensive than single-flow (usually ebb flow) directional systems. The working systems in Table 9.2 mainly use single-basin and two-way flow schemes.

Water to the high tide level is permitted to flow upstream through the turbines and sluices. This is retained in the basin until the ebbing tide has created a sufficiently large tidal range, and then released, through the turbines, downstream according to electricity demand. For water control purposes the upstream water behind the barrage can also be released through sluices without energising the turbines. Let the tidal range of water available be designated R, as in Fig. 9.14. If the surface area of retained water in the basin is A square metres, then

$$\text{Volume of water in the basin} = AR \tag{9.7}$$

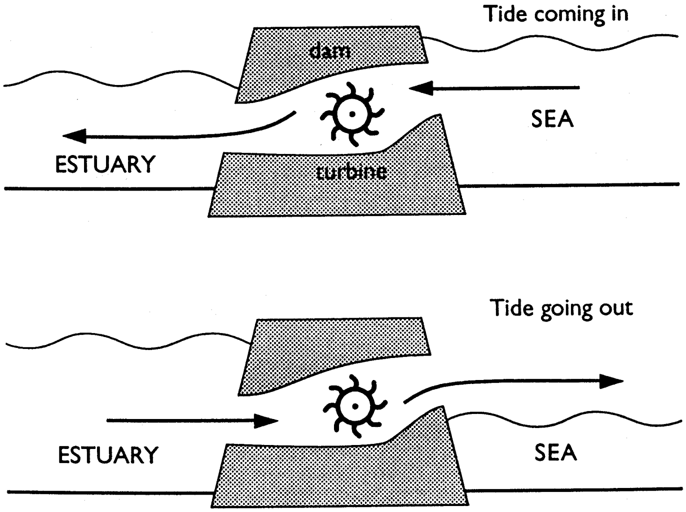


Fig. 9.13. Tidal power generation [9].

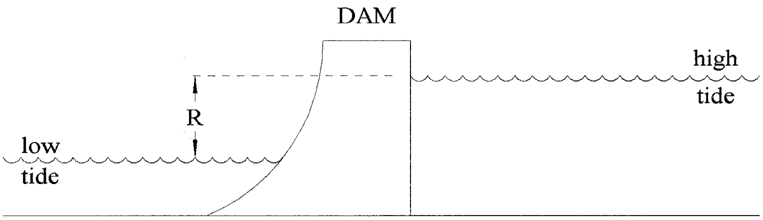


Fig. 9.14. Definition of "tidal range".

If the density of the water is ρ, then

$$\text{Mass of retained water} = \text{Volume} \times \text{density} = AR\rho \tag{9.8}$$

Now the force available due to controlled motion of the water is

$$\begin{aligned} \text{Force} &= \text{mass} \times \text{acceleration} \\ F &= AR\rho g \end{aligned} \tag{9.9}$$

where $g =$ gravitational acceleration constant. If losses are neglected, the potential energy (PE) of the retained water is equal to the work done by the water in flooding into or ebbing out of the dam basin

$$\begin{aligned} W &= \text{force} \times \text{distance} \\ \therefore W &= AR\rho g \cdot R/2 \end{aligned} \tag{9.10}$$

since $R/2$ is the mean vertical distance travelled by the water. It is convenient to rewrite (9.10) in a more compact form. For each tide

$$W = \frac{1}{2} \cdot \rho g A R^2 \tag{9.11}$$

It is clear from (9.11) that the tidal range R is the dominant design variable. Now the tide floods and ebbs twice during each tidal day so that there are four tides every 24.813 hours. The theoretical maximum power is therefore given by

$$P_{\text{max}} = \frac{4 \times \frac{1}{2}\rho g A R^2}{24.8 \times 3600} \tag{9.12}$$

If $\rho = 1000$ kg/m^3 and $g = 9.81$ m/s^2, then

$$P_{\text{max}} = 0.22AR^2 \text{ MW} \tag{9.13}$$

where A is km^2 and R is in metres.

Because of various losses, the power actually available is about 25% of the value implied in (9.12) and (9.13)

$$P_{\text{actual}} = \frac{P_{\text{max}}}{4} = 0.056AR^2 \tag{9.14}$$

Some numerical calculations involving (9.14) are given in Sec. 9.2.6.

9.2.3. *Costs of tidal barrage schemes*

The main cost of building a tidal barrage scheme is the cost of the dam or barrage across the bay. Roughly speaking, the cost of construction is proportional to the length of the dam wall, L. Since the extractable power is proportional to the basin surface area A, (9.14), good design requires the combination of low L and high A. A useful "figure of merit" in design is to minimise the value of the ratio L/A. Values of this ratio are given in Table 9.2 for the various active and proposed systems. If length L is in metres and area A is in square kilometres, the ratio L/A must be less than the value 80 for financial viability.

$$\frac{L}{A} < 80 \tag{9.15}$$

It is seen in Table 9.2 that the proposed Severn Barrage in the UK has a relatively high value $L/A = 50$. This reflects the high construction costs per unit energy output for a relatively small system.

The ratio of barrage length L in metres to the actual power delivered P_{actual} in megawatts is L/P_{actual} and should also be as small as possible.

9.2.4. *Combination of a pumped storage facility with a tidal barrage scheme*

A pumped storage system can be incorporated with a tidal barrage scheme by the use of a double water basin. Water can be released from the high level basin to the low level basin and out to the sea through two sets of generators. The system is illustrated diagrammatically in Fig. 9.15, where a head of water h exists over and above the value R due to the tidal range, in a basin of the same area.

The potential energy available during emptying of the tidal range R plus the pumped storage h is, by implication from (9.11),

$$\text{PE}_{\text{total}} = \frac{1}{2}\rho g A(R+h)^2 \tag{9.16}$$

The additional component of energy input that is needed to pump the water above the high tide level, to a level h metres, is

$$\text{PE}_{\text{pump}} = \frac{1}{2}\rho g A h^2 \tag{9.17}$$

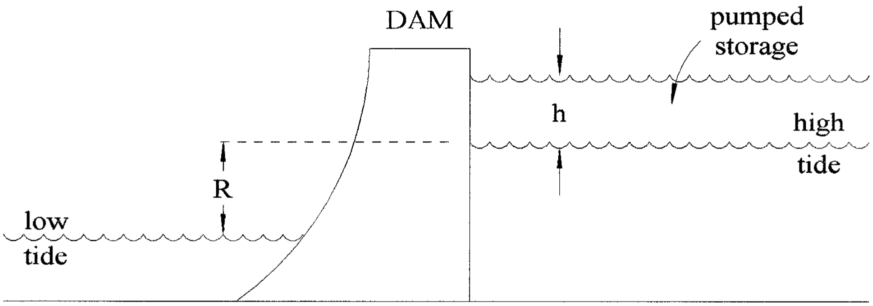


Fig. 9.15. Pumped storage contribution to tidal range.

Now the net gain of energy due to the use of pumped storage can be expressed as an energy balance equation

$$\begin{array}{l}\text{Net gain of}\\ \text{energy due to}\\ \text{pumped storage}\end{array} = \begin{array}{l}\text{Total energy}\\ \text{available in}\\ \text{the presence of}\\ \text{pumped storage}\end{array} - \begin{array}{l}\text{energy due to}\\ \text{tidal basin}\end{array} - \begin{array}{l}\text{energy input}\\ \text{to raise the}\\ \text{water level}\\ \text{to } h\end{array} \tag{9.18}$$

Substituting (9.11), (9.16) and (9.17) into (9.18) gives

$$W_{\text{net gain}} = \frac{1}{2}\rho g A[(R+h)^2 - R^2 - h^2] = \frac{1}{2}\rho g A[2Rh] \tag{9.19}$$

It is expressive to rewrite (9.19) in terms of the basic tidal energy equation (9.11)

$$W_{\text{net gain}} = \frac{1}{2}\rho g A R^2 \left[\frac{2h}{R}\right] \tag{9.20}$$

In order to gain the maximum benefit from the pumped storage addition, the ratio h/R must be made as large as possible.

If the pump-generator system has an efficiency of k per unit, the energy needed to pump the water into the storage area is increased. Equation (9.17) then becomes

$$\text{PE}_{\text{pump}\,k} = \frac{\frac{1}{2}\rho g A h^2}{k} \tag{9.21}$$

The net gain of energy is then

$$\begin{aligned} W_{\text{net gain}\,k} &= \frac{1}{2}\rho g A\left[(R+h)^2 - R^2 - \frac{h^2}{k}\right] \\ &= \frac{1}{2}\rho g A\left[2Rh + h^2\left(\frac{k-1}{k}\right)\right] \end{aligned} \tag{9.22}$$

The $(k - 1/k)$ term in (9.22) is negative for all $k < 1$. In terms of the basic tidal energy equation, (9.22) it can be rewritten as

$$W_{\text{net gain}\,k} = \frac{1}{2}\rho g A R^2\left[\frac{2h}{R} - \left(\frac{h}{R}\right)^2 - \left(\frac{1-k}{k}\right)\right] \tag{9.23}$$

When the efficiency is 100%, $k = 1$ and (9.23) reduces to (9.20). Numerical examples of pumped storage tidal schemes are given in Sec. 9.2.6.

9.2.5. *Features of tidal barrage schemes*

A large tidal barrage scheme is likely to have a major impact in its local area, in addition to providing a diversified supply of renewable energy for electricity generation. McVeigh [1] lists various relevant factors that are included in the following list.

(a) The *construction industry* would benefit from major contracts, involving much additional labour.

(b) *Manufacturing industry* in the vicinity of the water reservoir and its fill streams may need to adopt higher standards of cleanliness and effluent control.

(c) There would be vastly enhanced *recreational opportunities* (i.e. sailing, fishing, camping, etc.) in the region of the reservoir and barrage. For example, the reservoir basin of a Severn Barrage scheme in the UK could be developed into the largest water sports centre in Europe.

(d) A barrage across an estuary could carry a *public road* for vehicles and pedestrians.

(e) The *water levels*, both upstream and downstream of the barrage, could be affected.

(f) *Water flow rates upstream* of the barrage could be reduced, which might affect drainage and irrigation of the adjacent land.

(g) *Changed water flow rates downstream* of the barrage would affect the whole estuary. If effluent is now deposited directly or after treatment into the estuary, then its clearance to the sea might be reduced.

(h) The entire *aquatic ecosystem* will be affected by any changes of salinity or turbidity of the water.

(i) *Sedimentation* may occur. If it occurs in the basin there may be a reduction of basin volume. On the seaward side, sedimentation from upstream may stay deposited rather than be swept out to sea. Serious sedimentation could affect the navigability of any part of the waterway.

(j) The local *sea defences* would be enhanced. A barrage system would result in greater flood control and reduce the risk of storm damage along the estuary coastline.

(k) The *navigation* of ships would be affected. For example, the presence of locks could slow down the journey passage time. On the other hand, the deep water navigation channels might be more predictable.

(l) A total barrage across a river or estuary would affect the *migration routes for fish*. Swimming routes for fish upstream would likely be feasible through the sluices in ebb generation schemes. Swimming routes downstream would need the provision of channels to bypass the turbine ducts.

(m) The *permanent employment possibilities*, once the barrage is in operation, are limited. There would be a large work force during construction and this would move on after completion of the building work.

(n) In an environmentally aware world the *political kudos* for building a major clean, non-polluting, infinitely renewable source of electricity is considerable.

(o) Electricity is likely to remain the major preferred power source for both industrial and domestic markets. It is in the national interest to supplement the major (fossil fuel) generation with different sources of supply.

9.2.6. *Worked examples on tidal energy schemes*

Example 9.4

A small tidal energy scheme has a basin measuring 3 km times 20 km. If the average tidal range is 1.5 m, calculate the maximum electrical power available.

From (9.13) the maximum theoretical power is

$$P_{\text{max}} = 0.22 \times 3 \times 20 \times (1.5)^2 = 29.7 \text{ MW}$$

The actual power available, from (9.14), is one quarter of the theoretical value

$$P_{\text{actual}} = 0.056 \times 3 \times 20 \times (1.5)^2 = 7.42 \text{ MW}$$

Example 9.5

A tidal-power barrage scheme has a basin area of 50 square kilometres. The tidal range R, representing the difference between the high and low tide levels, is 11.5 metres. Both the ebb and flood tides can be harnessed for power raising and there are two tides in each tidal day of 24.814 hours. The density of sea water is 1000 kg/m^3 and the acceleration of mass due to gravity is 9.81 m/s^2.

(a) Calculate the total theoretical energy for each ebb or flood tide.
(b) If 25% of the theoretical energy is extractable, calculate the power generation capacity per day.
(c) What is the maximum length of dam wall that would be considered financially viable for this barrage area?

(a) The energy/tide is given by (9.11).

$$W = \frac{1}{2} \times 1000 \times 9.81 \times 50 \times 10^6 \times (11.5)^2 = 32.45 \times 10^{12} \text{ joules}$$

(b) Assuming that there are two tides/day and that both the ebb and flood tides are usable, then

$$P_{\text{max}} = \frac{4 \times \frac{1}{2}\rho g A R^2}{24.8 \times 3600} = 0.22 A R^2 \text{ MW}$$

If 25% of the power is extractable, then

$$P_{\text{actual}} = \frac{0.22}{4} \times 50 \times (11.5)^2 = 363.7 \text{ MW}$$

(c) For financial viability the inequality (9.15) must be applied

$$\frac{\text{length of wall (m)}}{\text{area of basin (km}^2\text{)}} < 80$$

In this case, $A = 50$ km^2 so that

$$\text{length of wall} < 80 \times 50 < 4000 \text{ m (2.49 miles)}$$

Example 9.6

A tidal barrage scheme has a tidal range of R metres. The scheme is to be enhanced by the addition of a pumped storage facility which effectively increases the basin height by h metres above the high tide level. If $h = R$ calculate the extent of the additional energy capacity of the enhanced scheme due to the pumped storage contribution.

The net gain due to pumped storage is given in (9.20). If $h = R$ it is seen that

$$W_{\text{net gain}} = \frac{1}{2}\rho g A R^2 \left[\frac{2h}{R}\right] = \frac{1}{2}\rho g A R^2 [2]$$

Due to the pumped storage component the net gain of energy is *twice* the original basin energy. In other words, the new basin energy is three times the original value.

Example 9.7

Recalculate the additional energy capacity of the pumped storage scheme of Example 9.6 if the pump motor operates at 50% efficiency.

In (9.23), $k = 0.5$. The net energy gain is therefore

$$W_{\text{net gain}} = \frac{1}{2}\rho g A R^2 \left[\frac{2h}{R} - \left(\frac{h}{R}\right)^2\right]$$

Since $h = R$, in this case, then

$$W = \frac{1}{2}\rho g A R^2 [2 - 1] = \frac{1}{2}\rho g A R^2$$

The result is equal to the basic energy gain per tide in (9.11). In other words, with a pump of such low efficiency as 50% the advantage of the pumped storage energy is neutralised by the pump losses, when $h = R$.

9.3. Wave Power

Ocean waves are generated by the wind. Since the wind energy is produced by solar energy, it follows that wave energy is an indirect form of solar energy. Local variations in wind velocity are compensated by short-term energy storage in the high inertia of the water. In effect, the ocean mass acts to significantly smooth out the effects of wind variations.

An estimate of the global annual average wave power in kW/m of wavefront is given in Fig. 9.16. The western coastline of the British Isles is the most favourable location in the world, considering both the wave power potential and the long coastline. More detail of this is given in Fig. 9.17, which shows the location of the UK ocean weather ship (OWS) *India*, south of Iceland. Wave power calculations in the UK are usually based on data collected by this Ocean Weather Station.

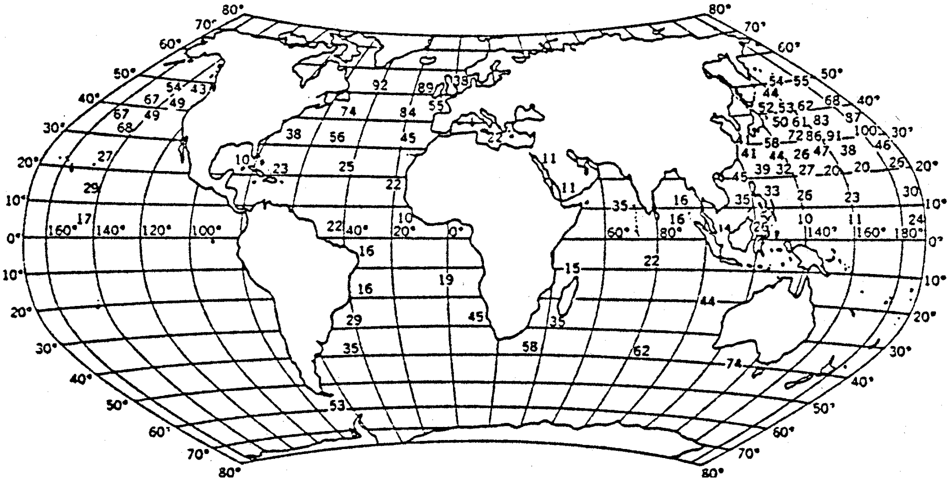

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Fig. 9.16. Estimate of global annual average wave power (kW per metre of wavefront) (Ref.: Tornkvist, Helsinki, Finland).

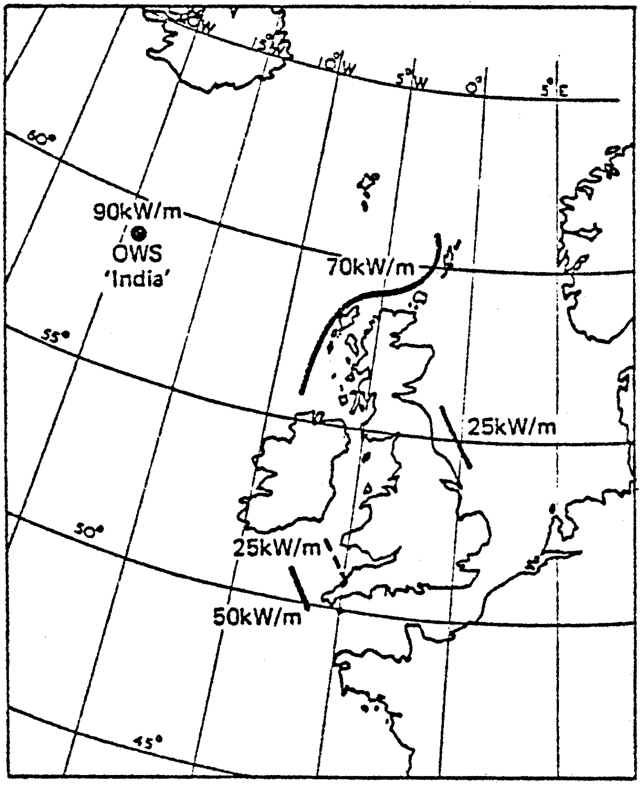
20°W
15°W
10°W
5°W
0°
5°E
60°
55°
50°
45°
90kW/m
OWS
'India'
70kW/m
25kW/m
25kW/m
50kW/m

Fig. 9.17. Position of ocean weather ship (OWS) *India* and likely wave power sites [6].

Measurements in the early 1980s showed that at UK inshore sites feasible for the deployment of wave energy devices, power levels of the order 40–50 kW/m were available in 50 m depth of water. Lower levels of 25 kW/m are available off the north-east coast of England and the south-west coast of Wales, Fig. 9.17. Power capabilities of this order are of considerable interest for electrical power generation.

9.3.1. *Basic properties of ideal deep-water waves* [5]

Proposed wave power systems are usually designed to operate in deep water, where the mean depth of the sea bed is greater than half a wavelength of the water wave. The surface waves are sinusoidal in nature. Individual particles of water describe circular paths, Fig. 9.18, of amplitude a that are independent of the wavelength λ. Usually $a < \lambda/10$. Although a wave progresses across the water surface, with horizontal velocity v, the individual particles describe their circular paths in a fixed location and do not progress.

Consider the ideal case of a sinusoidal wave of peak-to-peak amplitude H and wavelength λ travelling across the ocean surface at a horizontal velocity v, Fig. 9.18. The singular frequency f and periodic time T of this monochromatic wave are related to λ and v by

$$v = \lambda f = \frac{\lambda}{T} \tag{9.24}$$

If v is in m/s and λ in metres the frequency f has the dimension of reciprocal seconds (s^{-1}) or hertz. Let the angular frequency ω of the wave be given, as usual

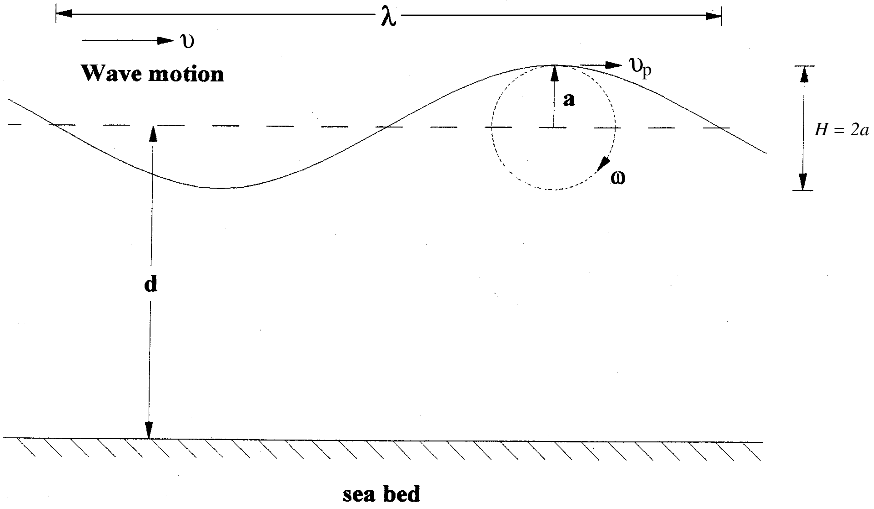

Fig. 9.18. Sinusoidal surface water wave.

with wave motions, by

$$\omega = 2\pi f = \frac{2\pi}{T} \tag{9.25}$$

Note that the angular frequency of the surface travelling wave ω is the same as the angular frequency of rotation of a particle path. The instantaneous velocity of a particle $v_p = a\omega$ at the top of its circular path, however, is not the same as the wave velocity v.

The wavelength of a surface travelling wave can be shown from wave theory to be, if $H \ll d$,

$$\lambda = \frac{2\pi g}{\omega^2} \tag{9.26}$$

Combining (9.25) and (9.26) gives an expression for the periodic time T in terms of wavelength.

$$T = \sqrt{\frac{2\pi\lambda}{g}} \tag{9.27}$$

In the North Atlantic, for example, the waves have periodic times of typical value 10 seconds. In (9.27) this corresponds to a wavelength of 156 m.

The horizontal component of the wave surface velocity can be obtained by combining (9.24), (9.25) and (9.26)

$$v = \frac{\omega\lambda}{2\pi} = \frac{\omega}{N} = \frac{g}{\omega} = \frac{gT}{2\pi} = g\sqrt{\frac{\lambda}{2\pi g}} \tag{9.28}$$

It is of interest to note that the velocity v is independent of the wave amplitude H.

A wave of fixed-value, single frequency, such as that of Fig. 9.18, is known as a monochromatic wave and is characterised by a property called the wave number N.

$$N = \frac{2\pi}{\lambda} = \frac{\omega}{v} \tag{9.29}$$

The total energy content W due to the equal components of potential energy plus kinetic energy, in each wavelength, per unit width of the wavecrest (i.e. the width of the wave perpendicular to the page in Fig. 9.18) of an individual wave is found to be

$$W = \frac{\rho g H^2}{8}\ \mathrm{J/m/}\lambda \tag{9.30}$$

For a wavelength λ the theoretical total energy content per metre of wavecrest width may be written as

$$W = \frac{\rho g H^2 \lambda}{8}\ \mathrm{J/m} \tag{9.31}$$

Combining (9.25), (9.26) and (9.31) gives other expressions for the total energy content per-unit wavecrest width.

$$W = \frac{\pi \rho g^2 H^2}{4\omega^2}\ \text{J/m} = \frac{1}{16\pi}\,\rho g^2 H^2 T^2\ \text{J/m} \tag{9.32}$$

The theoretical maximum power P_{ideal} corresponding to the total energy content, per-unit crest width, under ideal conditions, is obtained by dividing (9.32) by time T.

$$P_{\text{ideal}} = \frac{\rho g^2 H^2 T}{16\pi}\ \text{W/m} \tag{9.33}$$

Using the values $\rho = 1000\ \text{kg/m}^3$ and $g = 9.81\ \text{m/s}^2$, (9.33) gives

$$P_{\text{ideal}} = 1915 H^2 T\ \text{W/m}$$

A more useful form is

$$P_{\text{ideal}} = 1.915 H^2 T\ \text{kW/m} \tag{9.34}$$

9.3.2. *Power extractable from practical deep-water waves*

In any given location the resultant surface of the sea is called a dispersive wave and is due to a complicated combination of waves having different wavelengths, directions and time-phase displacements. The power extractable in the direction of the overall average wave motion, for random waves, can be shown mathematically to be one half of the power of an individual ideal wave. Although the waves are travelling across the water surface at an individual velocity v, defined in (9.28), the energy content of the group of waves is transmitted at only one half of this velocity. This "energy" velocity $v/2$ is sometimes called the group velocity.

From (9.31) the practical power extractable per metre of wavefront can be deduced to be

$$P_{\text{pract}} = \frac{1}{8}\,\rho g H^2 \cdot \frac{v}{2} \tag{9.35}$$

Because the average horizontal velocity v of ideal energy transmission is halved, the corresponding periodic time is doubled to $2T$.

If the ideal energy equation (9.32) is divided by $2T$ the theoretical average power content of the group of practical deep-sea waves is found to be

$$P_{\text{pract}} = \frac{W}{2T} = \frac{1}{32\pi}\,\rho g^2 H^2 T\ \text{W/m} \tag{9.36}$$

Using the values $\rho = 1000\ \text{kg/m}^3$ and $g = 9.81\ \text{m/s}^2$ in (9.36) gives a value for the theoretical group average power

$$P_{\text{pract}} = 0.96 H^2 T\ \text{kW/m} \tag{9.37}$$

But, in reality, even this reduced value is not available. In mid-ocean the resulting wave effect at a location is due to a combination of so many influences that it cannot be accurately calculated mathematically. With a complex, multi-variable situation like this the best way to determine the overall effect is to measure it repeatedly and use statistical data based on measured previous performance.

A set of data measured on-site by the UK ocean weather ship *India* is reproduced in Fig. 9.19 [5]. Each co-ordinate space represents a data reading and the number represents the average number of occurrences per 1000 samplings in the one-year experiment period. For example, at the intersection $H = 4$ m and $T = 9.25$ s is the number 19, which means that waves with these parameters were measured 19 times in the experimental period time. At the location of this weather station the measured power per metre of wave front is found to be

$$P_{\text{meas}} = 0.55H^2T \tag{9.38}$$

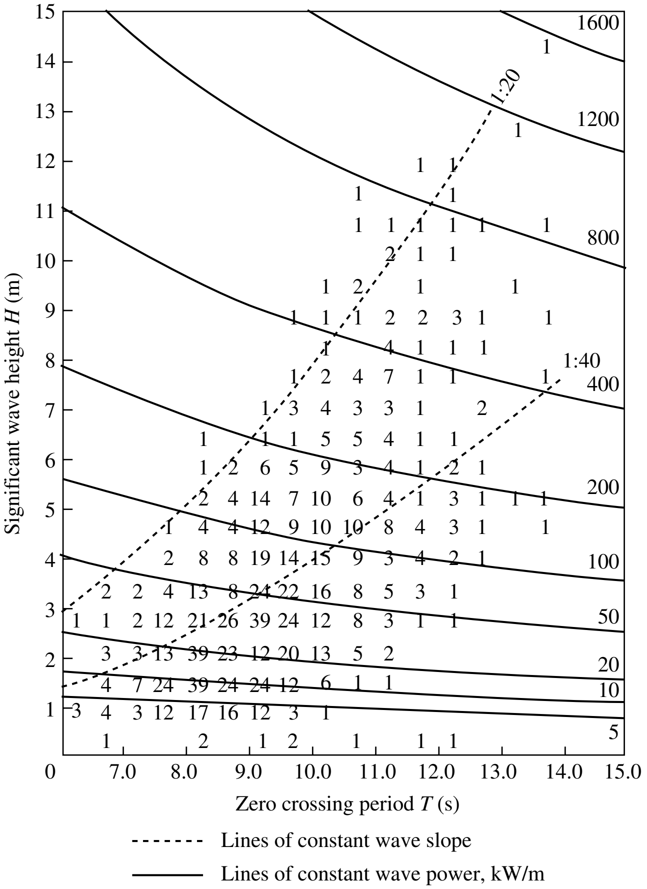

Fig. 9.19. Scatter diagram of wave height and frequency at OWS *India* [5].

This measured value of potential wave power is seen to be about 30% of the maximum value predicted by ideal wave theory in (9.34) and 57% of the more practical value given by (9.37). The data of Fig. 9.19 suggests that, in that particular location, waves of common incidence have values $T = 8$–10 s and $H = 2$–3 m, having an associated power of about 50 kW/m of wavecrest length. But the actual efficiency of extraction, incorporating outage time due to breakdown and maintenance, is likely to be about 30%. A reasonable estimate of the power actually extractable is therefore

$$\begin{aligned} P_{\text{extract}} &= 0.3P_{\text{meas}} \\ &= 0.3 \times 0.55H^2T \\ &= (0.16 - 0.2)H^2T \text{ kW/m} \end{aligned} \tag{9.39}$$

The power actually extractable is seen to be roughly 10% of the power content of an individual ideal wave, given in (9.34). Roughly speaking, waves from the Atlantic striking the western shorelines of Great Britain and Ireland have crest–trough values H of 2–4 m and a periodic time $T \approx 10$ s. The actual power extractable is obtained by substituting typical values into (9.39), giving

$$P_{\text{extract UK}} \approx 15\text{–}20 \text{ kW/m} \tag{9.40}$$

9.3.3. *Worked examples on wave energy*

Example 9.8

The periodic time of a typical North Atlantic wave is 10 s. Calculate the associated frequency, wavelength and velocity.

With $T = 10$ s, from (9.25)

$$\omega = \frac{2\pi}{T} = \frac{2\pi}{10} = 0.63 \text{ radians/s}$$

$$f = \frac{\omega}{2\pi} = \frac{0.63}{2\pi} = \frac{1}{10} \text{ Hz}$$

from (9.27),

$$\lambda = \frac{gT^2}{2\pi} = \frac{9.81 \times 10^2}{2\pi} = 156.1 \text{ m}$$

from (9.24),

$$v = \frac{\lambda}{T} = \frac{156.1}{10} = 15.61 \text{ m/s}$$

Example 9.9

The waves striking the shores of the western coast of Scotland contain an estimated theoretical maximum power of 70 kW/m of crest length. If a typical periodic time is 11 s, what is the corresponding wave height?

Using (9.34),

$$P_{\max} = 1.915H^2T \text{ kW/m}$$

The peak-to-peak wave height is therefore given by

$$H^2 = \frac{70}{1.915 \times 11} = 3.32 \text{ m}^2$$

$$\therefore H = \sqrt{3.32} = 1.82 \text{ m}\,(5.98 \text{ ft})$$

It should be noted, however, that only about 10% of the theoretical maximum power is likely to be extractable by wave-energy systems.

Example 9.10

What value is the extractable power from a deep-sea wave of wavelength 150 m and height 1.5 m if $g = 9.81$ m/s^2?

From (9.27),

$$T = \sqrt{\frac{2\pi\lambda}{g}} = \sqrt{\frac{2\pi 150}{9.81}} = \sqrt{96} = 9.8 \text{ s}$$

Using (9.39), if the trough–crest height is 1.5 × 2 = 3 m,

$$P_{\text{extract}} = 0.2H^2T \text{ kW/m} = 0.2(3)^2 9.8 = 17.64 \text{ kW/m}$$

This compares with the value, from (9.37),

$$P_{\text{pract}} = 0.96H^2T = 84.7 \text{ kW/m}$$

and the value, from (9.34),

$$P_{\text{ideal}} = 1.915H^2T = 169 \text{ kW/m}$$

The extractable power is seen to be 17.64/169 = 10.4% of the total power capacity of an ideal water wave.

9.3.4. *Types of wave power converters*

Most of the wave-energy conversion devices and systems that have been actively considered consist of structural elements that move due to the water wave motion. Energy is extracted from the waves and is converted to electrical power by the relative motions and forces between different elements of the structures. These various forms of wave-energy converter are aligned in wide rows perpendicular to the incident wave direction. The size and geometry of a design must be appropriate for the range of water waves experienced at the particular location.

The best-known wave-energy converter is the Salter duck [1, 10, 11]. Duck sections, Fig. 9.20, are mounted along a fixed central spine. Each section has an asymmetric cam which extracts energy by semi-rotary motion, about the fixed spindle, in response to the incident water waves.

The cam is profiled so that its front surface moves with the water of the oncoming wave, while the back surface does not disturb the water behind. It therefore absorbs energy from the approaching waves but does not transmit a wave behind it. In motion, the bobbing up and down of the cam tails is very similar to a flock of ducks on the water. To be practical, under sea conditions, a Salter duck would require a wave frequency $\omega = 0.8$ radians/s. From (9.25) this corresponds to a wave periodic time $T = 2\pi/\omega = 8$ s. The duck structure would then need to be the large estimated

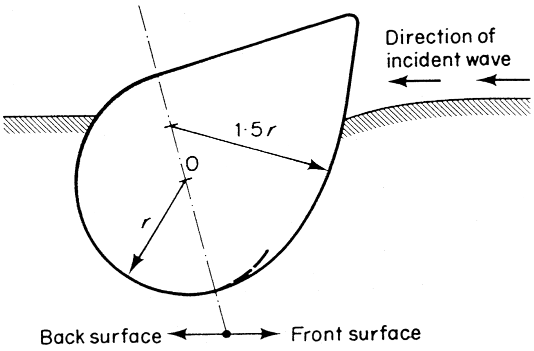
Direction of incident wave
1·5r
O
r
Back surface
Front surface

Fig. 9.20. Principle of the Salter duck [11].

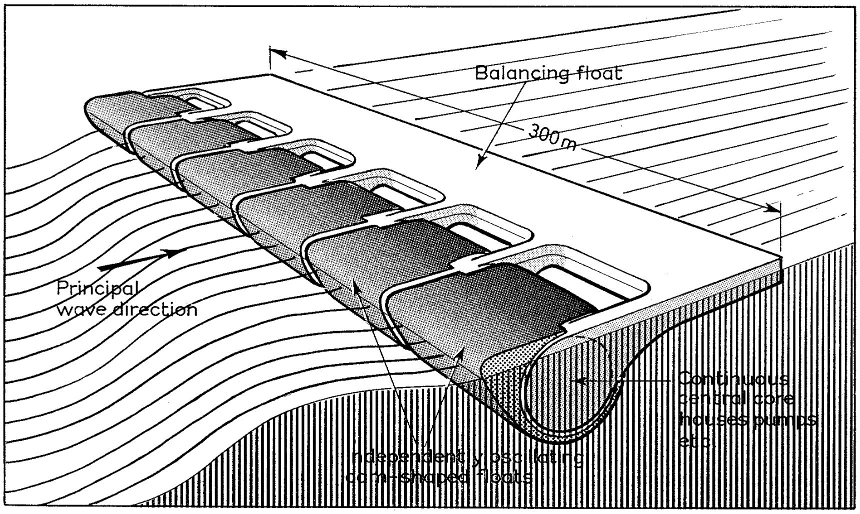
Balancing float
300m
Principal wave direction
Continuous central core houses pumps etc.
Independently oscillating cam-shaped floats

Fig. 9.21. Salter duck assembly for large-scale power generation [12].

value of 15 m in diameter and would be very expensive to engineer, Fig. 9.21 [12]. This scheme is probably best thought of as future technology rather than present technology.

Another UK invention is the Cockerell raft, which consists of a structure of floating rafts or pontoons. Adjacent rafts are hinged and relative motion between the rafts is used as a source of mechanical power, Fig. 9.22. To be used in realistic sea conditions, the two hinged rafts would need to be between 80 and 120 m long. The displacement per metre length of structure is then likely to be 100–200 tonnes of steel and concrete. This obviously represents a major engineering project, involving a great use of raw materials, high energy use in fabricating the structure and skilled engineering in constructing the system and retrieving its collected energy. The Cockerell raft is probably too expensive to have any serious prospect of large-scale implementation.

Scale model tests have been performed on both the Salter and Cockerell systems but no high power implementation has yet taken place, nor is likely to do so.

A further range of proposed designs involves the oscillations of columns of water. The vertical motion of the contained water, Fig. 9.23, due to wave action causes compression of the air above it, as in a diving bell, and the compressed air can be used to power a turbine [13]. An experimental prototype has been in operation on the shoreline of Islay, Scotland, since 1991. The wave-energy converter is built into a natural rock gully. Water in the concrete housing, Fig. 9.23, rises and falls like a piston forcing air in and out of the capture chamber through a Wells turbine. Electrical output powers of 60 kW have been obtained and delivered to the national grid in calm sea conditions, and up to 600 kW short-term output during severe storms.

The most promising of the offshore wave-energy projects appears to be the Sea Clam, developed at the University of Coventry, UK [14]. A flotilla of flexible air bags are attached to the face of a moored floating spine, Fig. 9.24, which is the stabilising component. Compressed air created by the wave action is forced from the bags through a turbine housing into and out of the hollow spine, allowing interchange of air between the clam bags. Each clam element has only two moving parts: the air bags, which are proposed to be manufactured using a type-cord reinforced fabric, and the turbo-generator rotor. The basic structure would be unmanned and simple but robust. Since the working fluid is compressed air in a closed circuit, there is no risk of equipment damage due to contamination by sea water.

A specification for a clam unit to deliver up to 10 MW of power would require the unit to be 275 in (902 ft) long, with an external section about 15 m by 13 m. An artist's drawing of a clam section, Fig. 9.25, clearly shows the turbine channel and illustrates the necessary vast scale of structure. Large-scale application of the clam would involve the use of many such 10 MW devices, each of which has a displacement of 44,000 tonnes.

Many other forms of wave-energy machines have been proposed. Some of these are fixed and massive immovable structures, mounted on the sea bed, designed to capture large volumes of water for use in water turbines. In common with the

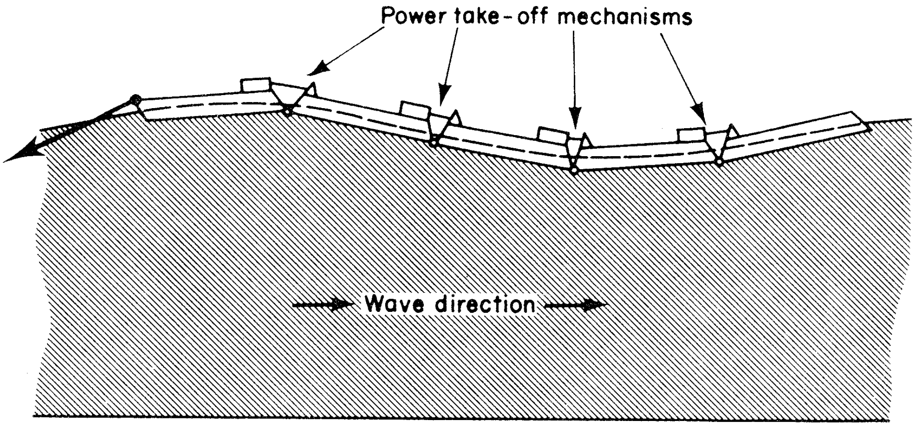
Power take-off mechanisms
Wave direction

Fig. 9.22. Cockerell wave contouring raft [1].

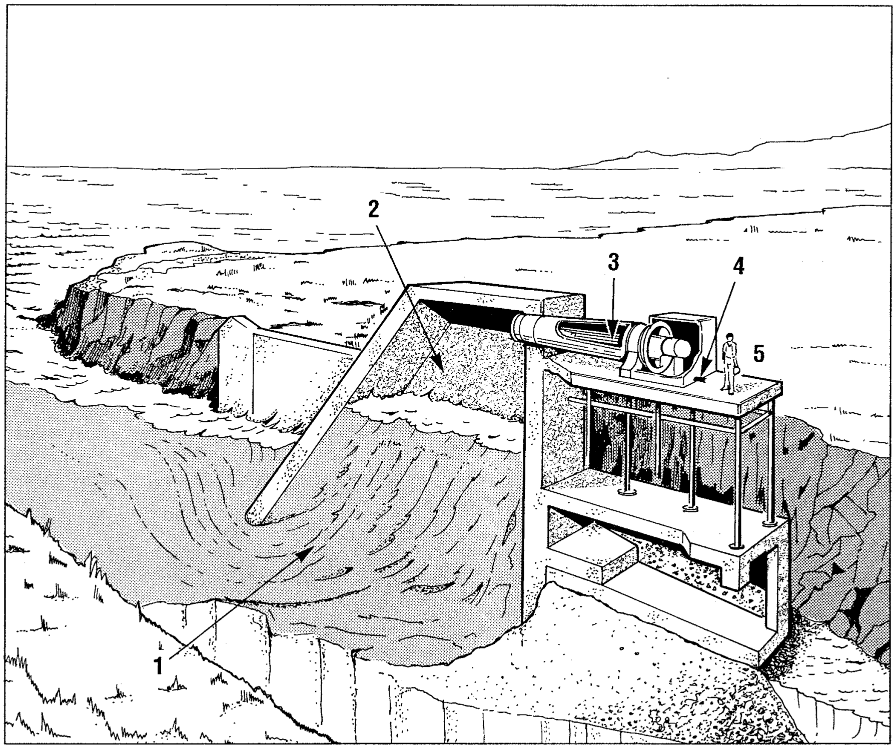

Fig. 9.23. Islay shoreline wave device [9, 13].
(1) Piston action of the wave motion.
(2) Alternative compression and expulsion of air.
(3) Air turbine rotation.
(4) Generated electricity piped to grid.
(5) Human operator.

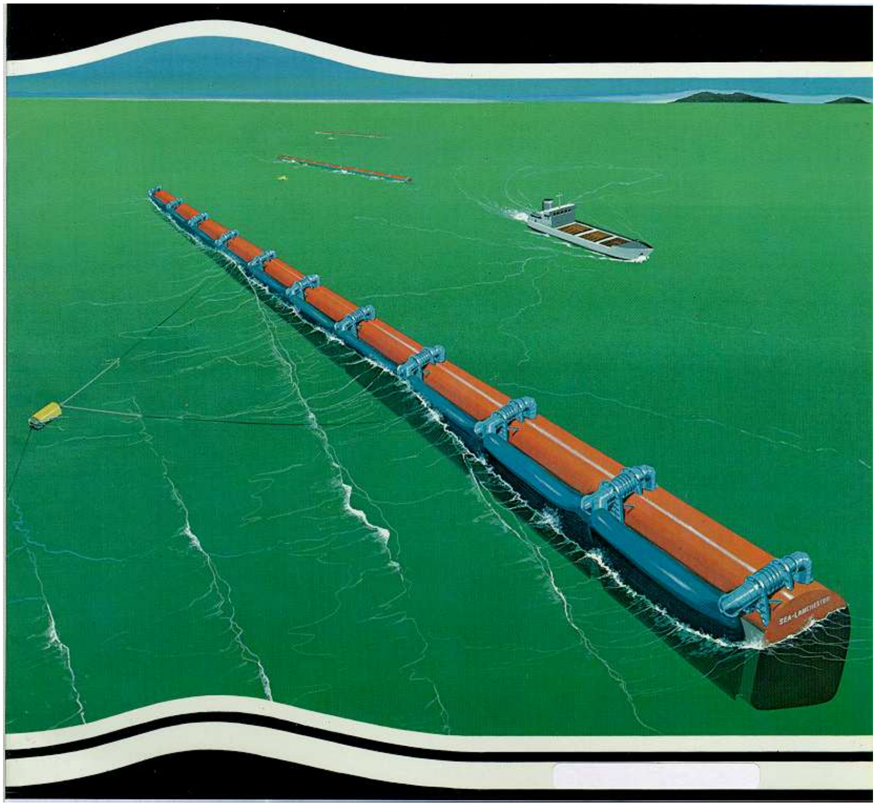

Fig. 9.24. Artistic impression of sea-clam assembly [14].

relative motion systems of Salter and Cockerell and compressed air methods such as the Sea Clam and the Oscillating Water Column, however, they largely remain expensive, small-scale experimental prototypes or ingenious ideas that have never been tested at all.

9.3.5. *Worked examples on wave-energy devices*

Example 9.11

It is estimated that a realistic figure for the power extractable from water waves along the western coastlines of Scotland and Ireland is about 20 kW/m length of the wave power capture system. What length of ideal wave power extractor, aligned perpendicularly to the incoming waves, would be required to realise a power of 3 MW, equivalent to that of the Orkney wind turbine system?

The Orkney wind power system is designed to deliver a rated load of 3 MW of electrical power. In order to match this from a wave power system the necessary energy-capturing structure would need to have

$$\text{Length} = \frac{3 \times 10^6}{20 \times 10^3} = 150 \text{ m} = 496 \text{ ft}$$

For example, the Salter converter assembly of Fig. 9.19 is shown having a capture length of 300 m. This would extract up to 6 MW of wave power, but be subject to various losses.

Example 9.12

The Cockerell raft and the Sea Clam systems for wave-energy capture and conversion involve constructions of displacement about 150 tonnes per metre of capture length. A realistic value for the extractable power from the waves, in a favourable location, is 20 kW/m. What length of ideal extractor structure would be needed to realise 1 MW of power and what is the structure displacement?

$$\text{Required length} = \frac{10^6}{20 \times 10^3} = 50 \text{ m}$$

At a rate of 150 tonnes/m the corresponding displacement of structural materials is

$$\text{Displacement} = 50 \times 150 = 7500 \text{ tonnes}$$

Example 9.13

A proposed Sea Clam wave-energy converter system consists of separate units, each 275 m long, which can realise up to 10 MW of power. How many clam units and what approximate length of coastline would be needed to generate 1000 MW of power?

To generate 1000 MW, if all the units were in operation and working to capacity, would require

$$\text{Number of clam units} = \frac{1000 \times 10^6}{10 \times 10^6} = 100 \text{ units}$$

If each unit was sited end-to-end this would require a sea length of

$$\text{Length of clam units} = 100 \times 275 = 27{,}500 \text{ m} = 27.5 \text{ km}$$

It is highly probable, however, that there would be generous spacing between the units to permit the passage of boats and to prevent shading effects. Since the units are all arranged to be at the same small angle to the sea-wave fronts (illustrated in Fig. 9.24), the overall length of the barrage of converters might be about 50 km. Therefore

$$\begin{aligned}\text{Length of coastline} &\approx 50 \text{ km}\\ &\approx 50 \times 0.62 = 31 \text{ land miles}\\ &\approx 50 \times 0.54 = 27 \text{ nautical miles}\end{aligned}$$

In a practical engineering situation it is likely that (say) one third of the clam units might be inoperative because of repair or maintenance. This implies that there would need to be one third more units occupying one third more space. A more realistic estimate of the requirements for 1000 MW generation is therefore

$$\begin{aligned}\text{Number of units} &\approx 130\text{–}140\\ \text{Length of coastline} &\approx 65\ \text{km}\\ &\approx 40\ \text{miles}\end{aligned}$$

9.3.6. *Features of wave power systems — summary*

No large-scale, floating, wave power installations have yet (2002) been built. Although there can be no dispute about the amount of potential energy available in the waves, there is much misgiving about the viability of extracting the energy. In particular, the large size of the necessary structures and the financial costs of construction and implementation are formidable. Some of the implications of the use of large-scale wave-energy schemes are listed below [1]. The features are not listed in order of significance but in an arbitrary order.

(a) The seas, around Great Britain in particular, frequently represent a *hostile environment*. It would be necessary for the wave-energy structures to be extremely strong, rugged, heavy and expensive.
(b) Fouling of the structures due to *salt water* pollution could be a serious problem, requiring ongoing maintenance.
(c) The turbine and generator systems would require *ongoing maintenance*. A wave power structure would not provide suitable living accommodation.

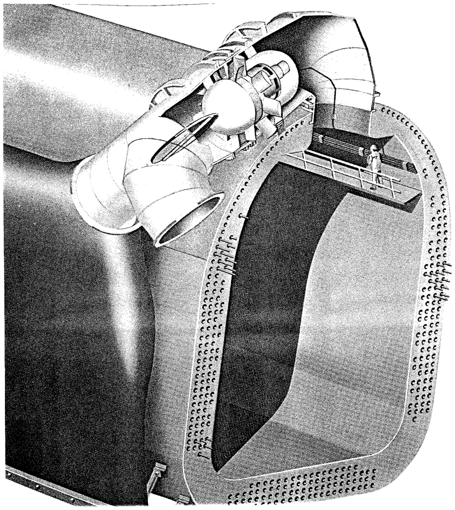

Fig. 9.25. Artistic impression of sea-clam section [14].

Servicing of the structures would have to be carried out by shore-based personnel. Difficulties of access to the rigs would be encountered due to bad weather.

(d) *Ecological effects* would be experienced at the shoreline due to the changed energy of the waves reaching the shore.

(e) A rate of extractable power of the order 20 kW/m, (9.40), ideally corresponds to about *1 MW for 50 m of wavefront.* In order to generate power of a few MW (i.e. the order of power available from a large wind turbine system) the structure would require to be 100–200 m in length. This would be a massive construction with a displacement weight between 10,000 and 20,000 tonnes, or about the displacement of a small cargo ship or a small oil tanker.

(f) The necessary large structures may require *vast amounts of steel and concrete in their construction.* These raw materials are energy-intensive in their industrial preparation. In other words, there would be a large energy investment to be repaid before the rig operated at an energy profit.

(g) A structure of useful size for generating electricity would have a *large visual impact* if it was close to shore. Example 9.13 shows that a 1000 MW system would occupy roughly 40 miles of coastline.

(h) A structure of useful size for generating electricity would be a *navigational hazard* to shipping. Sea lanes would need to be planned, marked by buoys and continuously monitored.

(i) A wave-energy converter structure could *limit the access of fishing boats* within its vicinity, and/or interfere with the trawling process.

(j) The *deposition of particles* along the local leeward shore or on the sea bed might be affected.

(k) The overall conclusion is that wave-energy extraction is likely to be formidable in its difficulties. At the present period (2002) it does not appear, to the authors, to be an attractive option.

9.4. Ocean Currents and Underwater Turbines [15, 16]

Although the seas and oceans are in constant motion, the velocities of the motion in most locations are far too slow to offer useful levels of power. Intense and suitable power densities can be found where currents are accelerated between islands or around headlands. Seawater is 832 times the density of air. The kinetic energy available from a 5-knot ocean current is equivalent to the very large wind velocity of 270 km/h (168 mph). A water current of 4.5 knots (2.25 mph) has a power density of about 6 kW/m, while a windstream of over 40 knots (20 m/s) would be needed to realise a similar power density. A typical marine current turbine can have a rotor-swept area of diameter only 40% the value of a wind turbine of the same rating. Although a rotor for extracting energy from flowing water can be readily designed and built, the difficulty of installing it securely is great. Much research

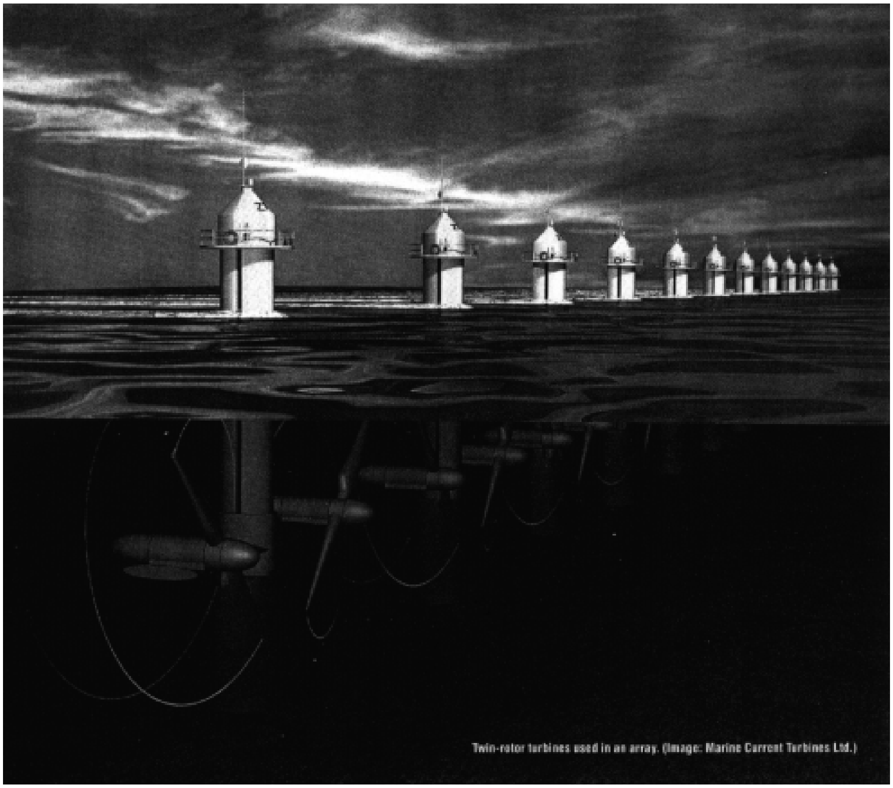
Twin-rotor turbines used in an array. (Image: Marine Current Turbines Ltd.)

Fig. 9.26. Artistic impression of underwater turbines [15].

and feasibility exploration is going on all over the world. One such topic, from the UK, is illustrated in Fig. 9.26 [15].

9.5. Problems and Review Questions

Problems on Hydroelectricity

9.1. From the information in Table 9.1, list the half-dozen countries that consumed the most hydroelectric power in 2000.

9.2. In which countries has the consumption of hydroelectric power (a) increased, (b) decreased, most significantly in the period 1990–2000?

9.3. What was the proportion of the world total primary energy consumption taken by hydroelectricity in the year 2000?

9.4. A hydroelectricity supply system has an overall efficiency of 82%. If the effective head of water is 500 m, calculate the volumetric flow rate needed to generate 300 MW of electric power.

9.5. Show that, if losses are neglected, the velocity of the water striking the blades of a hydroelectric turbine is proportional to the square root of the head height, independently of the flow rate.

9.6. The volumetric flow rate of water in a hydroelectric scheme is 50 m^3/s. The overall efficiency of the turbine, generator and pumped storage motor is 72%. If the electric power output is to be 150 MW, what head of water is required? ($\rho = 1000\ \text{kg/m}^3$, $g = 9.81\ \text{m/s}^2$.)

9.7. What types of water turbine would be likely to be used in locations where the available head of water is: (a) 10 m, (b) 100 m, (c) 1000 m?

9.8. The mean height of the feeder reservoir in the Dinorwig pumped storage hydroelectric scheme is 568 m. At rated load the overall efficiency is 86%. If the plant operates for 5 hours, delivering 1750 MW, what mass of water has passed through the turbines? What has been the flow rate?

9.9. [Adapted from Ref. 5] Estimate the hydroelectric potential of an area or location, chosen from an atlas giving geophysical data. Use the following technique, having chosen location X.

(i) What is the lowest altitude of X?
(ii) What area of X lies more than 300 m above the lowest level?
(iii) What is the annual rainfall on the high parts of X?
(iv) If all of the rainfall ran to the lowest level, what amount of potential energy per year in MW would be given up by the moving water?
(v) What factors would prevent all of the rainfall being converted to electricity?
(vi) Estimate the fraction of the rainfall potential energy that might be convertible to electricity.
(vii) If your selection location X already contains a hydroelectric power station, compare your estimate of its potential power capacity with the station rating. Comment on any large differences.

Problems on Tidal Power Schemes and Pumped Storage Schemes

9.10. List the advantages and disadvantages of a tidal barrage scheme as a source of electrical power.

9.11. In a pumped storage scheme combined with a tidal power project, water is pumped from the high tide level to an additional height of 1 m. The tidal range R is 6 m. Calculate the proportion of extra energy gained: (a) neglecting losses, (b) if the pump motor is 80% efficient.

9.12. If the efficiency of the pump-motor in a pumped storage tidal system is fixed in value at any level k below 100%, show that the net energy gain will be a maximum when $h = kR/(1 - k)$.

9.13. The mean tidal range of the Rance scheme is 8.45 m and its basin area is 22 km^2, as given in Table 9.2. If the mean output is 75 MW, what proportion of the theoretical power capacity does this represent?

9.14. Calculate the electrical power output from the proposed Severn estuary tidal power scheme in Britain if the mean tidal range is 8.8 m and the basin area is 50 square kilometres.

9.15. A certain tidal power scheme has a water basin with a V-shaped vertical cross-section. Show that the theoretical maximum power capability, for ebb-tide operation, is proportional to the cube of the maximum depth of water.

9.16. In North America the Bay of Fundy-Passamaquoddy area near the border of New Brunswick and Nova Scotia in Canada, with Maine in the USA, is considered to be a prime tidal power site. It has a basin area of 700 km^2 with an average tidal range of 10.8 m. Calculate the theoretical maximum power capability and the estimated realistic power available.

Problems on Wave Energy

9.17. For a monochromatic (single frequency) water wave of period 8.5 s, calculate the corresponding frequency, wavelength and velocity of the wave motion.

9.18. If the water wave of Problem 9.14 has a crest–trough height of 4 m, calculate the theoretical power and the realistic extractable power from a random group of such waves.

9.19. What is the power extractable from a deep-sea wave system of wavelength 140 m and height 3 m?

9.20. The western coast of Scotland is incident by Atlantic waves of theoretical maximum power 70 kW per metre of wave width. If a typical wave height is 2 m, what are the corresponding frequency and periodic time? Estimate the realistic power available onshore.

9.21. List and briefly discuss the main features of proposed wave power systems.

9.22. Estimate the necessary length of a proposed wave power receiver station to collect 10 MW of usable power if the maximum theoretical power is 70 kW/m.

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CHAPTER 10

WIND ENERGY

10.1. Background and History

Energy from the wind is derived largely from solar radiation. Motion of the air mass in the atmosphere is caused by solar insolation and is reproduced as jet streams. These affect the ground speed (but not necessarily the air speed) of high-flying jet aeroplanes. The disturbance of atmospheric air is reproduced at ground level as wind.

Like solar energy, the wind energy is free, environmentally clean and is infinitely renewable. There is no pollution and no direct use of fossil fuels in the energy-gathering process. Unlike solar energy, the wind availability is not cyclic and diurnal but intermittent, unpredictable and is not limited to daylight hours.

The wind has been used as an energy source for thousands of years, all across the world. Very early wind machines were vertical axis structures and have been identified in China, India, Afghanistan and the Middle East, especially Persia, going back to about 250 BC. Most of the earliest machines were used for pumping water in irrigation projects.

Horizontal axis wind machines were developed by the Arab nations and their use became widespread throughout the Islamic world. In Europe the horizontal axis machine became established about the 11th century AD, mostly of the form of a tower and sails, which became known as the Dutch windmill. In medieval England wind machines were used for grinding or milling grain and became known as windmills. The operators of windmills in feudal England took the designation of their craft and acquired the surname of Miller.

By the 18th century, multi-sail Dutch windmills were extensively used in Europe. It is estimated that by 1750 AD there were 8000 windmills in operation in Holland and 10,000 in Germany. Dutch settlers built wind machines in North America, mainly along the eastern coast areas that became the New England states of the USA. At one stage the shore of Manhattan Island was lined with windmills built by Dutch settlers [1].

Wind energy provided the motive power for sailing ships for thousands of years, until the age of steam. The fortunes of the European colonial powers such as England, France, Spain, Holland, Belgium and Portugal rested on their mastery of the sea and its navigation. The intermittent nature and uncertain availability of the wind and the relative slowness of wind-powered vessels gradually gave way to fossil-fuel-powered commercial shipping. Today this invariably uses oil-fuelled diesel engines. However, yachting and small boat sailing remain important recreational sports throughout the world.

The principal features of the classical type of Dutch windmill are illustrated in Fig. 10.1 [2]. Usually there are four sails located upstream (i.e. facing into the wind). The effective sail area can be modified by the use of shutters which can act to moderate the rotational speed and prevent overspeeding in high wind conditions. This is equivalent to furling the sails on a yacht. In later designs the cupola on top of the tower can rotate, under the guidance of a rudder or stabiliser wheel, so that the sails remain upstream and facing square-on to the wind direction. Mechanical rotational power obtained from the sail shaft is transmitted down the tower, via a bevelled toothed bearing, onto a vertical drive shaft. This in turn drives a toothed wheel system which supplies power to the grinding wheels for the corn.

In Fig. 10.1 the height of the rotating horizontal axis from the ground is often called the "hub height". For a typical windmill this might be 30, 40 or even 50 ft high. In spite of such a large structure, the power rating of this Dutch windmill is the mechanical equivalent of only a few tens of kilowatts. The power developed by this large structure is therefore roughly equivalent to the electrical power supply required by a large family house in Europe or North America. In engineering terms the efficiency of a Dutch windmill is low although this may be a secondary consideration since the input power is free.

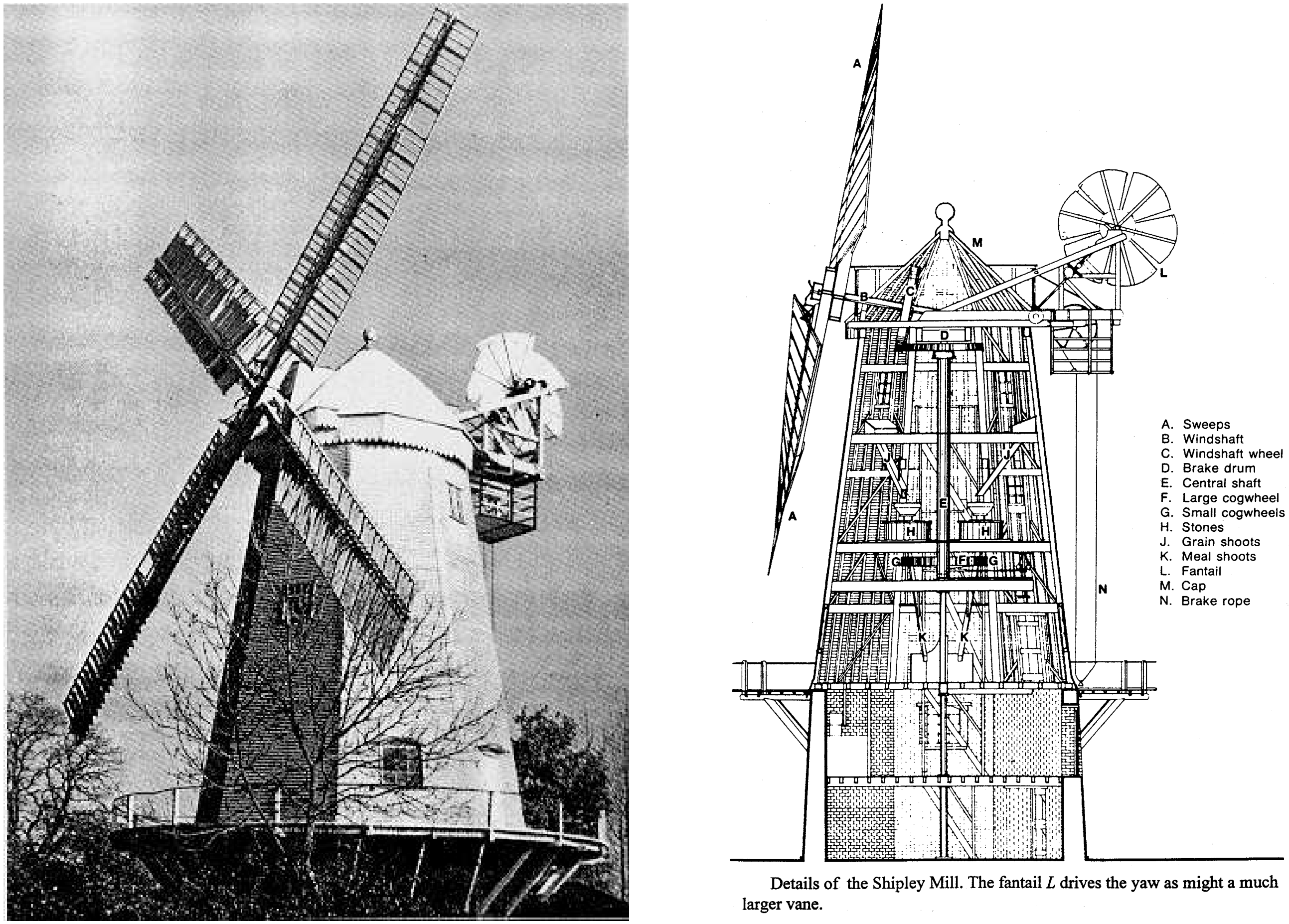
Wind energy is transmitted by what is essentially a low density fluid. The physical dimensions of any device used to convert its kinetic energy into a usable form are necessarily large in relation to the power produced.

10.2. Availability of Wind Supply

In most locations there is a characteristic pattern of wind velocity over the year. Although there may be significant variations of wind on a daily (sometimes hourly) basis, with regard to both magnitude and direction, the annual features are fairly consistent. This knowledge is an essential prerequisite to any serious consideration of the use of wind power for electricity generation.

10.2.1. *Wind energy supply in Europe*

Average annual wind speeds for Europe are shown in Fig. 10.2. The British Isles, consisting of Great Britain (England, Scotland, Northern Ireland and Wales) and


A
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H
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J
J
K
K
L
M
N
A. Sweeps
B. Windshaft
C. Windshaft wheel
D. Brake drum
E. Central shaft
F. Large cogwheel
G. Small cogwheels
H. Stones
J. Grain shoots
K. Meal shoots
L. Fantail
M. Cap
N. Brake rope

Details of the Shipley Mill. The fantail *L* drives the yaw as might a much larger vane.

Fig. 10.1. Shipley Wind Mill, Sussex, England [2] (built in 1879).

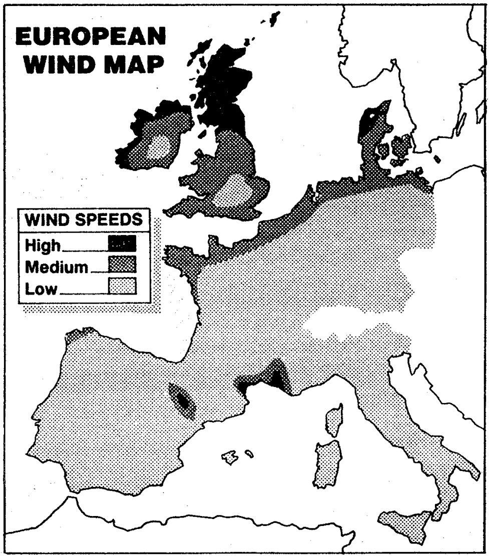
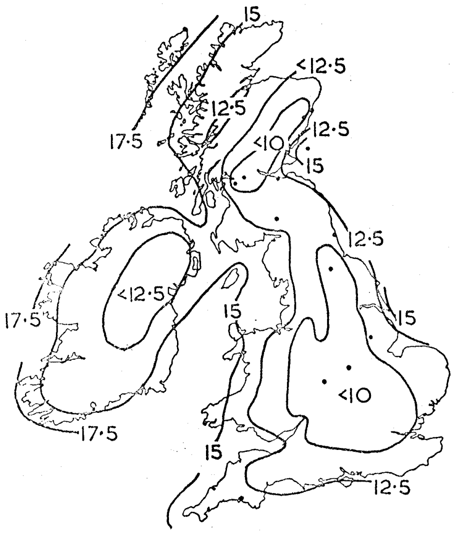

EUROPEAN WIND MAP
WIND SPEEDS
High
Medium
Low

Fig. 10.2. European wind atlas at 50 m above ground level [3].


15
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12·5

Fig. 10.3. Isovent contours of UK mean wind speed (mph) [4] (courtesy of the UK Meteorological Office).

the Republic of Ireland, form one of the windiest regions on earth. Contours of the mean annual wind speed, measured at the agreed standard height of 33 ft (10 m) above the ground, are given in Fig. 10.3 [4]. The wind speed increases greatly at higher levels. Wind speeds are defined in terms of the Beaufort scale, shown in

Table 10.1. Beaufort scale of wind velocities [5].

Description of wind	Observation	Speed, mph
Calm	Smoke rises vertically.	0–1
Light air	Smoke drifts slowly.	1–3
Light breeze	Wind felt on face. Leaves rustle.	4–7
Gentle breeze	Leaves and small twigs in constant motion. Flags or streamers extend.	8–12
Moderate breeze	Raises dust. Small branches move.	13–18
Fresh breeze	Small trees begin to sway.	19–24
Strong breeze	Large branches in motion. Umbrellas difficult to hold.	25–31
Moderate gale	Whole trees in motion.	32–38
Fresh gale	Breaks twigs off trees. Difficult to walk.	39–46
Strong gale	Slight structural damage to roofs and signs possible.	47–54
Full gale	Trees uprooted. Considerable structural damage occurs.	55–63
Storm	Widespread damage	64–72

Table 10.1 [5]. In general the coastal areas are windier than inland areas. The prevailing wind is westerly, from the Atlantic ocean, creating the high average value of 17.5 mph along the western coastlines of Scotland and Ireland. Incidentally, the same regions offer a great potential for water wave energy, as discussed in Chapter 9.

Tremendous local variations of wind energy occur even in a relatively small country like Great Britain. In Fig. 10.4 units of wind power are plotted against hours of wind availability per year for three different locations. It should be noted that a characteristic of power versus time means that the area under the curve has the dimension of power multiplied by time, which is energy. For wind energy use, the power versus availability characteristic should contain the largest possible area. In Fig. 10.4 the preferred location is obviously at Rhossili Down, which is on the west coast of Scotland.

There are important seasonal variations in the availability of wind energy. In northern temperate latitudes the highest daily average wind speeds occur in winter, with the maximum values usually being in January, and the lowest in July/August. The seasonal variation between winter and summer is of the order 2:1. The wind energy flux density on a typical month-by-month basis for the UK is given in Fig. 10.5. It is of immense significance that the availability of wind energy in the UK closely matches the national demand for electricity, shown in Fig. 3.7 of Chapter 3. It is also relevant that the profile of UK wind energy input is in antiphase with the profile of solar radiation input.

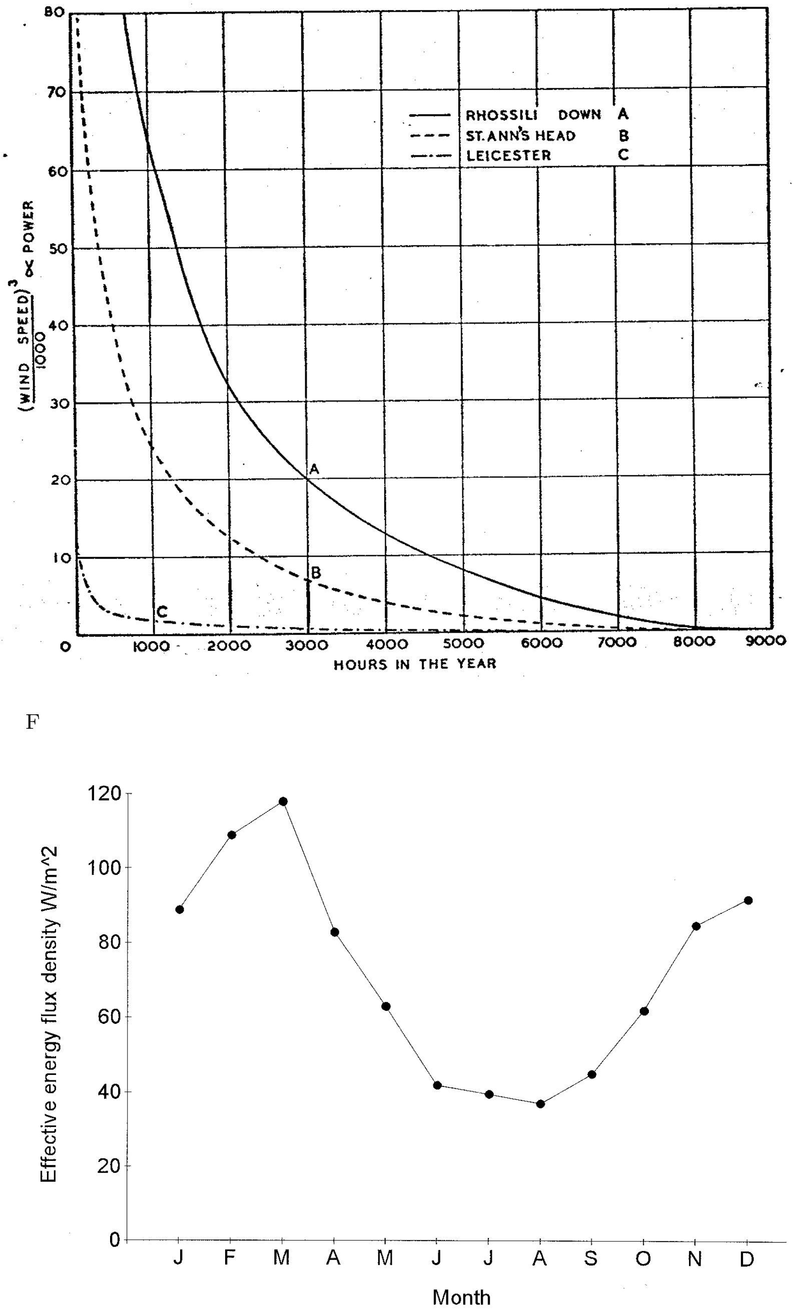


Fig. 10.5. Wind availability in the UK (mean wind velocity = 6 m/s = 13.4 mph).

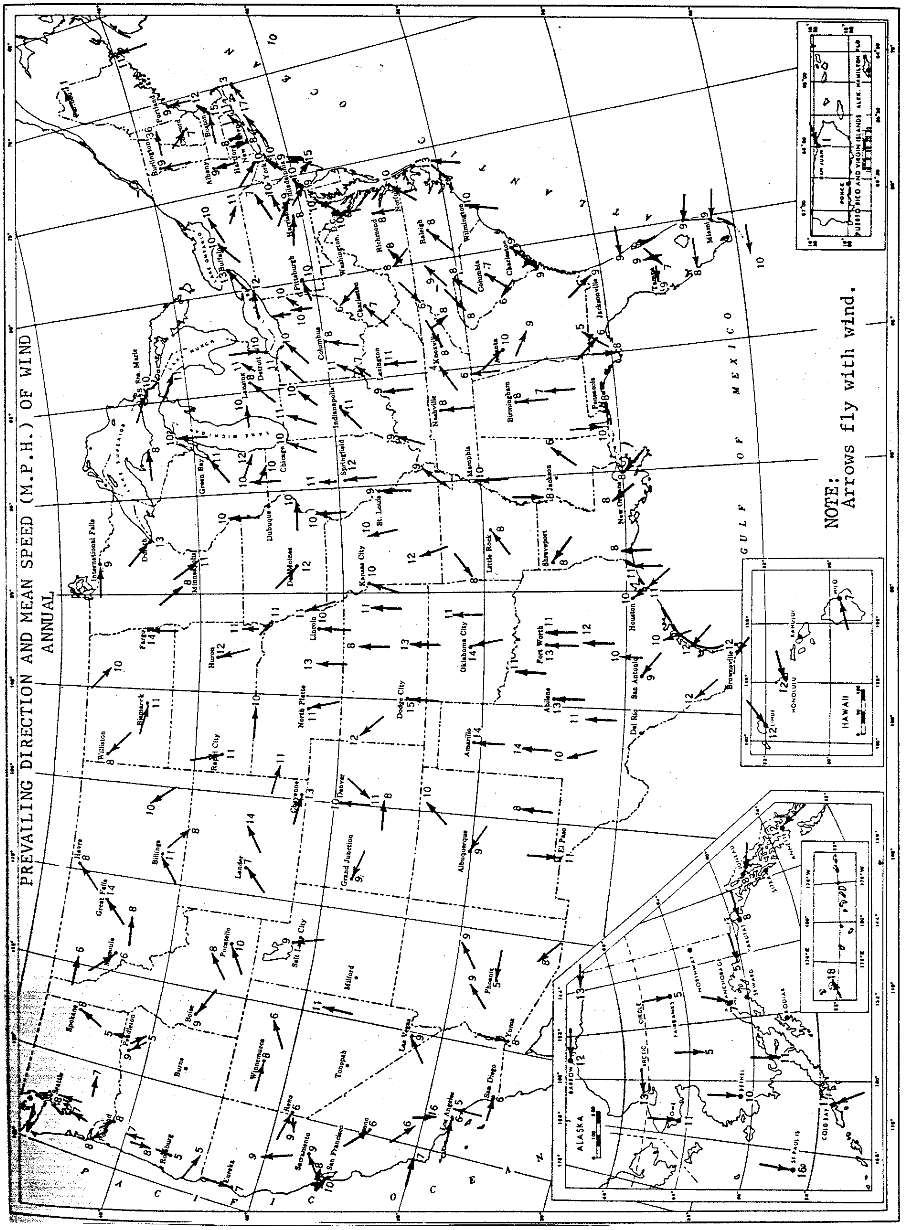

PREVAILING DIRECTION AND MEAN SPEED (M.P.H.) OF WIND
ANNUAL
NOTE:
Arrows fly with wind.
GULF OF MEXICO
PACIFIC OCEAN
ATLANTIC OCEAN
ALASKA
HAWAII
PUERTO RICO AND VIRGIN ISLANDS

Fig. 10.6. US wind atlas (courtesy of the US Meteorological Office).

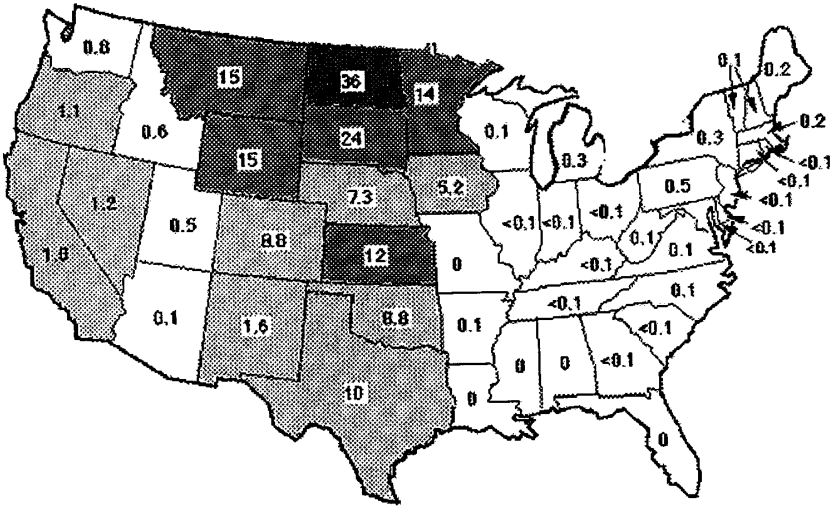


Fig. 10.7. Electrical energy potential of the wind as a percentage of the total US electricity consumption, 1990 [6].

10.2.2. *Wind energy supply in the USA*

The mean annual wind speed across the USA is shown in Fig. 10.6. The predominant feature is the southerly winds blowing north through Texas to North Dakota, along the entire N–S dimension (about 1500 miles). This is reflected in the electrical energy wind potential of the group of states in the middle and western parts of the country shown in Fig. 10.7 [6]. Many of the gulf and eastern states of the USA have no significant wind potential at all. Virtually all of the potential is concentrated in the 15 states shaded in the figure.

10.3. Theoretical Power Available in the Wind

The wind is a motion of a mass of air. If the air mass is m and it moves with an average velocity V, the kinetic energy (KE) of the wind is

$$\mathrm{KE} = \frac{1}{2} m V^2 \tag{10.1}$$

Consider the wind passing perpendicularly (normally) through an area A with thickness x of any shape, Fig. 10.8. If the air flow is smooth, free from eddies, and has a density (mass per unit volume) of ρ, then

$$\text{Mass of air contained in the element} = m = \rho A x \tag{10.2}$$

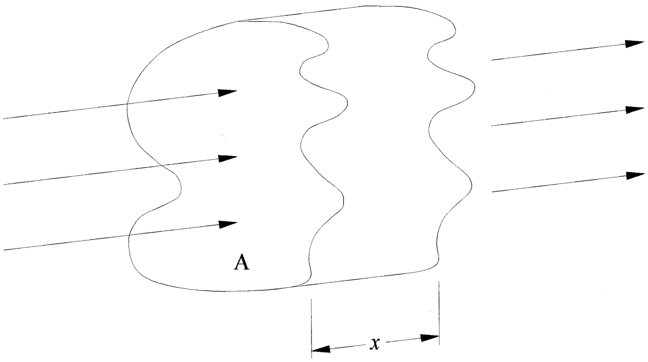


Fig. 10.8. Element of space through which the air flow passes.

Combining (10.1) and (10.2) gives a further expression for the kinetic energy of this volume and mass of wind

$$\mathrm{KE} = \frac{1}{2}\rho A x V^2 \tag{10.3}$$

The kinetic energy passing through the element per unit time is the power rating

$$P_w = \frac{d}{dt}(\mathrm{KE}) = \frac{1}{2}\rho A V^2 \frac{dx}{dt} \tag{10.4}$$

But the time rate of change of displacement dx/dt is the wind velocity V

$$\frac{dx}{dt} = V \tag{10.5}$$

The power in the wind is therefore from (10.4) and (10.5),

$$P_w = \frac{1}{2}\rho A V^3 \tag{10.6}$$

Equation (10.6) is the basis of all wind power and energy calculations. The most significant feature is that the wind power is proportional to the average velocity cubed. It is obvious that wind speed is therefore the dominant consideration in wind machine location.

The air density ρ varies with altitude and with atmospheric conditions such as temperature, pressure and humidity. At sea level and at standard temperature and pressure (STP),

$$\rho = 1.201\ \mathrm{kg/m^3}, \quad \begin{array}{l}\text{at 1000 millibars (29.53 in of mercury}\\ \text{or 101.3 kilo-Pascal (kPa)) and 293 K.}\end{array}$$

A table showing the reduction of atmospheric temperature, pressure and density with elevation is given in Table 10.2. For wind turbine applications the range of interest is mostly within a couple of hundred feet of ground level. There is a lot of local variation of values of air density in different areas of the world.

Table 10.2. Variation of atmospheric temperature, pressure and density with elevation [7].

Height (m)	Temperature (C)	Pressure (hPa)	Density (kg/m^3)
0000	15.0	1013	1.2
1000	8.5	900	1.1
2000	2.0	800	1.0
3000	−4.5	700	0.91
4000	−11.0	620	0.82
5000	−17.5	540	0.74
6000	−24.0	470	0.66
7000	−30.5	410	0.59
8000	−37.0	360	0.53
9000	−43.5	310	0.47
10000	−50.0	260	0.41
11000	−56.5	230	0.36
12000	−56.5	190	0.31
13000	−56.5	170	0.27
14000	−56.5	140	0.23
15000	−56.5	120	0.19
16000	−56.5	100	0.17
17000	−56.5	90	0.14
18000	−56.5	75	0.12
19000	−56.5	65	0.10
20000	−56.5	55	0.088
21000	−55.5	47	0.075
22000	−54.5	40	0.064
23000	−53.5	34	0.054
24000	−52.5	29	0.046
25000	−51.5	25	0.039
26000	−50.5	22	0.034
27000	−49.5	18	0.029
28000	−48.5	16	0.025
29000	−47.5	14	0.021
30000	−46.5	12	0.018
31000	−45.5	10	0.015
32000	−44.5	8.7	0.013
33000	−41.7	7.5	0.011
34000	−38.9	6.5	0.0096

In the UK, a useful figure is

$$\rho = 1.29 \text{ kg/m}^3 \ (0.08 \text{ lb/ft}^3) \tag{10.7}$$

In the USA a commonly quoted figure is

$$\rho = 1.275 \text{ kg/m}^3 \tag{10.8}$$

at sea level, under dry conditions at a temperature 0°C.

Table 10.3. Power available in the wind [4].

Power	Area	Velocity	Power equation
kW	m^2	m/s	$P = 0.000647\ AV^3$
HP	ft^2	mph	$P = 0.0000071\ AV^3$

Expressions for the power in the wind P_w from (10.6) are shown in Table 10.3 for two sets of units. With 1 m^2 of area one obtains 81 W of power at velocity 5 m/s and 648 W at 10 m/s.

10.4. Theoretical Maximum Power Extractable from the Wind

Only a fraction of the total theoretical power available in the wind, (10.6), is extractable. It is an intrinsic property of physical systems that when energy is converted from one form to another, the efficiency of the conversion is restricted by certain natural limitations.

Let a flow of smooth, steady air with an upstream velocity V_1 impinge upon the rotor of a wind machine, as illustrated in Fig. 10.9. Some of the energy from the wind is transferred to the wind machine so that the smooth, steady air far downstream flows at a smaller velocity V_2. The energy reduction of the flowing air mass m per unit time is

$$\text{Kinetic Energy} = \frac{1}{2}mV_1^2 - \frac{1}{2}mV_2^2 = \frac{1}{2}m(V_1^2 - V_2^2) \tag{10.9}$$

In the process of extracting air from the wind, the wind velocity V_r that actuates the rotor is less than the upstream "free wind" velocity V_1. With an ideal, lossless system, all of the energy reduction in the airstream is transferred to the rotor of the wind machine. The downstream velocity V_2 is then smaller than the actuating

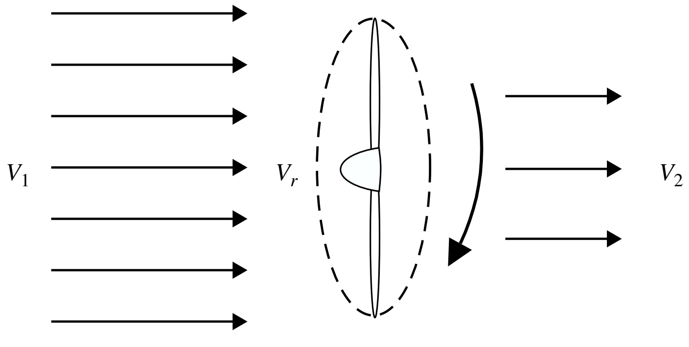


Fig. 10.9. Rotor of a wind converter.

velocity V_r. By equating the rate of change of kinetic energy (10.9) with the power absorbed in the associated rate of change of momentum, which is $m(V_1 - V_2)V_r$, it can be shown that

$$V_r = \frac{V_1 + V_2}{2} \tag{10.10}$$

Combining (10.2) and (10.5) gives the mass of air transferred per unit time

$$\frac{dm}{dt} = \rho AV \tag{10.11}$$

From (10.9) and (10.11) it is seen that the extracted power P_{ex} is

$$P_{\text{ex}} = \frac{d(\text{KE})}{dt} = \frac{1}{2} \cdot \frac{dm}{dt}(V_1^2 - V_2^2) = \frac{1}{2}\,\rho AV(V_1^2 - V_2^2) \tag{10.12}$$

Substituting (10.10) into (10.12) gives

$$P_{\text{ex}} = \frac{1}{4}\,\rho A(V_1 + V_2)(V_1^2 - V_2^2) = \frac{1}{4}\,\rho AV_1^3\left[1 + \frac{V_2}{V_1} - \left(\frac{V_2}{V_1}\right)^2 - \left(\frac{V_2}{V_1}\right)^3\right] \tag{10.13}$$

The value of V_2/V_1 that results in maximum power transfer is obtained by differentiating $dP_{\text{ex}}/d(V_2/V_1)$ from (10.13) and equating to zero. The resulting quadratic equation shows that to maximise P_{ex}, the ratio V_2/V_1 is either -1 or $+1/3$. Since the negative term is meaningless, the correct solution is

$$\frac{V_2}{V_1} = \frac{1}{3} \tag{10.14}$$

Substituting (10.14) into (10.13) gives

$$P_{\text{ex}_{\text{max}}} = \frac{8}{27} \cdot \rho AV_1^3 = \left(\frac{16}{27}\right)\frac{1}{2}\,\rho AV_1^3 = (0.593)\frac{1}{2}\,\rho AV_1^3 \tag{10.15}$$

The very important result of (10.15) is sometimes referred to as Betz' law. This states that "even with ideal wind energy conversion, the maximum power transferrable is only 0.593 or 16/27 of the total power in the wind". The theoretical maximum power available from an ideal wind machine is given in Table 10.4 [4]. It is quite striking how large a circular swept area must be used to generate any useful amount of power. For example, in a 10 mph wind, which is a light breeze, a swept area of 25 ft diameter would only realise the maximum theoretical value of 1.5 kW. This immediately points to the difficulty of using wind energy for domestic use in urban areas — the sail area or swept area required is too large to be practicable.

Table 10.4. Maximum theoretical power extractable by ideal wind machine [4].

$(0.593 \cdot \frac{1}{2}\rho AV^3)$

	Power (kW) from circular areas of different diameter (ft)				
Wind speed (mph)	12.5	25	50	100	200
10	0.38	1.5	6	24	96
20	3.08	12.3	49.2	196	784
30	10.4	41.6	166.4	666	2664
40	24.6	98.4	393.6	1574	6296
50	48.2	192.8	771.2	3085	12,340
60	83.2	332.8	1331	5325	21,300

10.5. Practical Power Extractable from the Wind

10.5.1. *Power coefficient*

The power actually available to drive a practical wind machine is much less than the theoretical maximum value defined in (10.15). A practical wind machine, often called a wind turbine, experiences air drag on the blades and friction of the air on the blades causing heat losses. In addition, the rotation of the rotor causes swirling of the air, which reduces the torque imparted to the blades. The net effect of the various losses is incorporated into a parameter called the power coefficient C_p. With an upstream air velocity V_1, the extractable power can be written as

$$P_{\text{ex}} = C_p \cdot \frac{1}{2}\rho AV_1^3 \tag{10.16}$$

where parameter C_p is seen from (10.12) to be the dimensionless variable

$$C_p = \frac{1}{2}\left[1 + \frac{V_2}{V_1}\right]\left[1 - \left(\frac{V_2}{V_1}\right)^2\right] \tag{10.17}$$

For the ideal theoretical case, when $V_2/V_1 = 1/3$, it has a maximum or Betz' law value of 16/27 or 0.593, but for practical wind turbines its value is usually in the range $0 \leq C_p \leq 0.4$. With the typical value $C_p = 0.4$, for example, it is seen that the power available in the wind is 0.4/0.593 or about 67% of the ideal theoretical value. Power coefficient C_p has a value that depends on the wind velocity, turbine rotational velocity and turbine blade parameters such as the pitch angle.

A propeller type of wind turbine will only start up at a certain minimum wind speed (which is usually about 8 mph or $8 \times 0.447 = 3.58$ m/s). For reasons of mechanical safety and to avoid structural damage, a wind machine can only operate up to a maximum design value of rotational speed, which is associated with the rated wind speed. If the rated wind speed is exceeded, either the pitch of the blades must be adjusted to limit the rotational speed or the rotor must be turned out of the

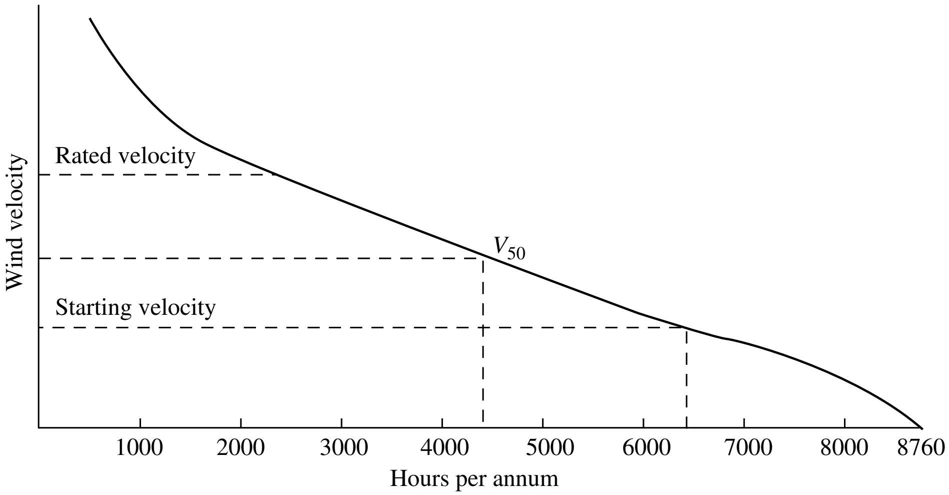


Fig. 10.10. Wind velocity duration curve for a selected UK site [1].

wind (i.e. furled) altogether. A typical characteristic of UK wind velocity versus hours of wind availability is given in Fig. 10.10 [1]. The ratio of rated velocity to starting velocity is usually between 2 and 3.

The wind velocity exceeded for 50% of the year (4380 hours) is denoted V_{50} in Fig. 10.10. This value is close to (but different from) the mean annual wind speed. If a wind turbine whose swept area has a diameter D metres is mounted directly onto a generator shaft, the annual extractable energy W has been estimated as [8]

$$W = 3.229D^2(V_{50})^3 \text{ kWh} \tag{10.18}$$

It should be noted that expression (10.18) was not derived by scientific deduction from basic equations. Rather, it represents an empirical interpretation of measured data that has been found to give accurate results.

The actual power available in a smooth, steady-flowing windstream is illustrated in Fig. 10.11 for a typical power coefficient $C_p = 0.4$ [9]. Both of the axes in Fig. 10.11 are graduated logarithmically. The scales of the figure illustrate both the large size of swept area and the high wind speeds needed in order to generate large amounts of power. For example, to obtain 100 kW of power in a strong wind (15 m/s) requires 100 m^2 of collector area.

10.5.2. *Axial thrust (pressure)*

The action of the wind onto the rotating propeller creates a pressure force acting along the shaft, called the thrust, which can be shown to have the value

$$\text{Axial thrust} = \frac{1}{2}\rho A V_1^2 \left[1 - \left(\frac{V_2}{V_1}\right)^2\right] \tag{10.19}$$

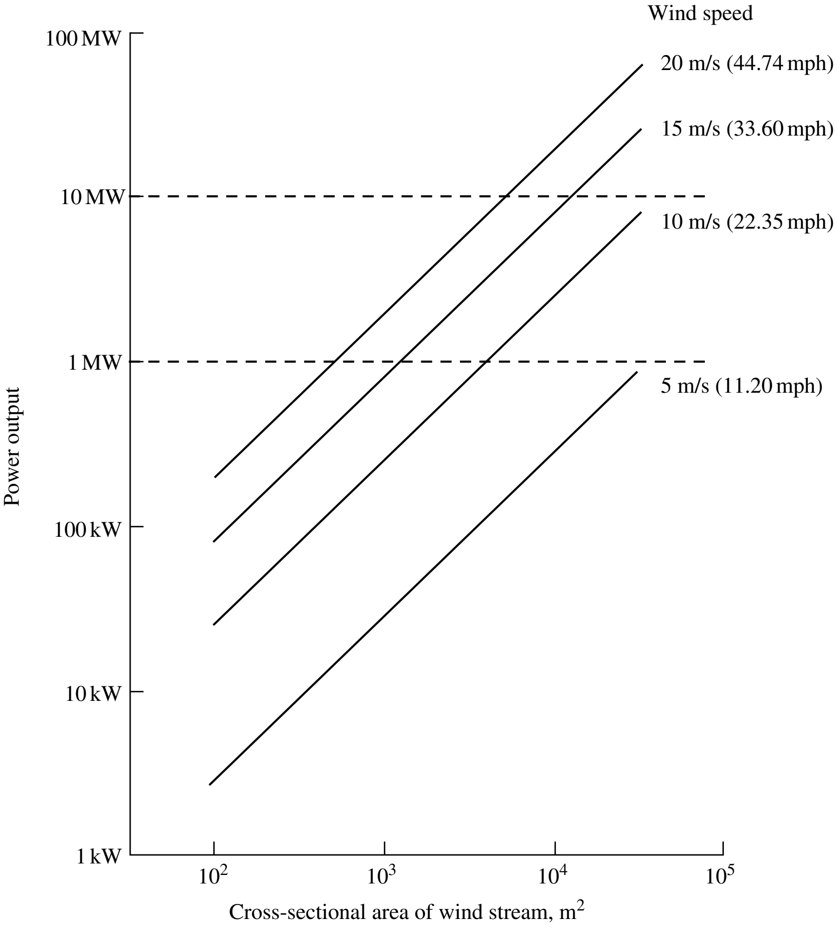


Fig. 10.11. Power extractable from a freely flowing windstream ($C_p = 0.4$) [9].

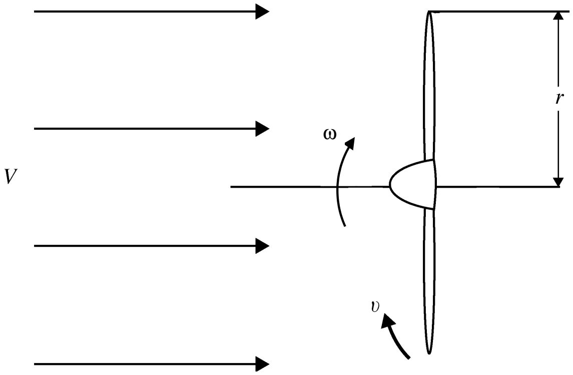


Fig. 10.12. Motion of a two-blade propeller.

The axial thrust acts to try and topple the turbine but is counteracted by the foundation of the structure.

10.5.3. *Tip-speed ratio (TSR)*

In order to express the power coefficient C_p in terms of both the upstream wind velocity V (rather than use of the terminology V_1) and the blade rotational velocity ω, a parameter called the tip-speed ratio (TSR) is defined. With reference to Fig. 10.12, v is the instantaneous velocity in m/s of the blade tip, tangential to its rotational motion, and ω is the angular velocity in radians per second. For a blade radius r metres the TSR is defined as

$$\mathrm{TSR} = \frac{r\omega}{V} = \frac{v}{V} \tag{10.20}$$

With a rotational velocity of n rpm

$$\omega = \frac{2\pi n}{60} \tag{10.21}$$

If C_p is plotted against V there is a different characteristic for every value of ω. Also, with C_p plotted against ω there is a different characteristic for every value of V. Good design requires that the maximum value C_{pm} occur near to the rated value of rotational speed. The variation of power coefficient C_p versus the TSR is a

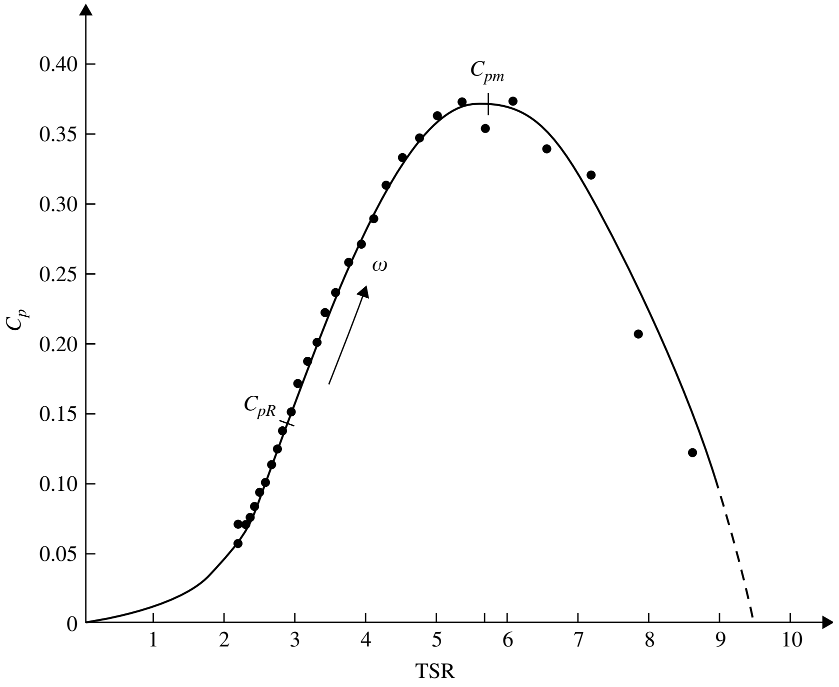


Fig. 10.13. Power coefficient versus tip-speed ratio for Darrieus and propeller machines [10].

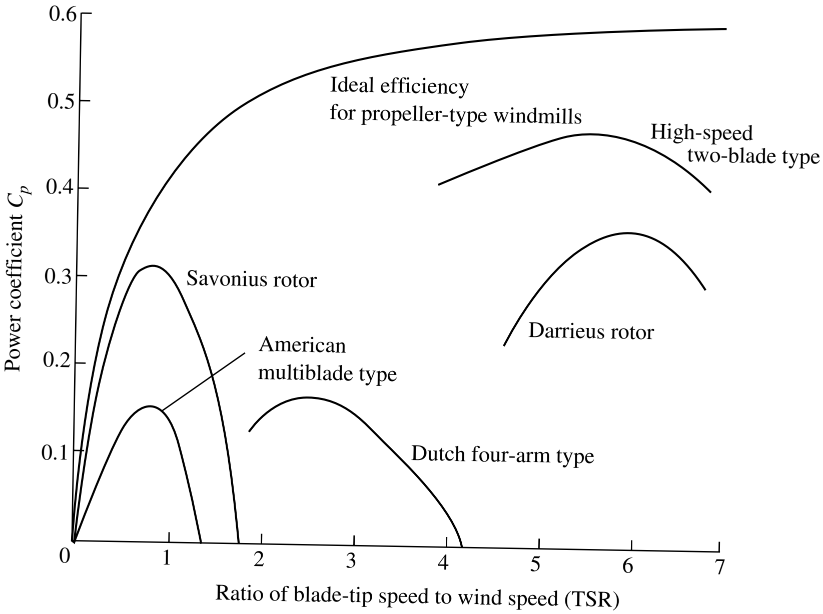


Fig. 10.14. Power coefficient versus tip-speed ratio for various converters.

"universal" characteristic for a wind turbine, incorporating both the V and ω features. All horizontal axis propeller machines and Darrieus machines (see Sec. 10.8) have similar types of characteristic, of the form of Fig. 10.13 [10]. A more comprehensive range of C_p versus TSR characteristics is given in Fig. 10.14. Of the many forms of wind machine now available, the two-blade propeller appears to result in the highest power coefficient, although this is disputed by some designers of other types of wind machine. High performance wind turbines have a TSR in the range of 5–6 at rated speed.

10.5.4. *Solidity factor*

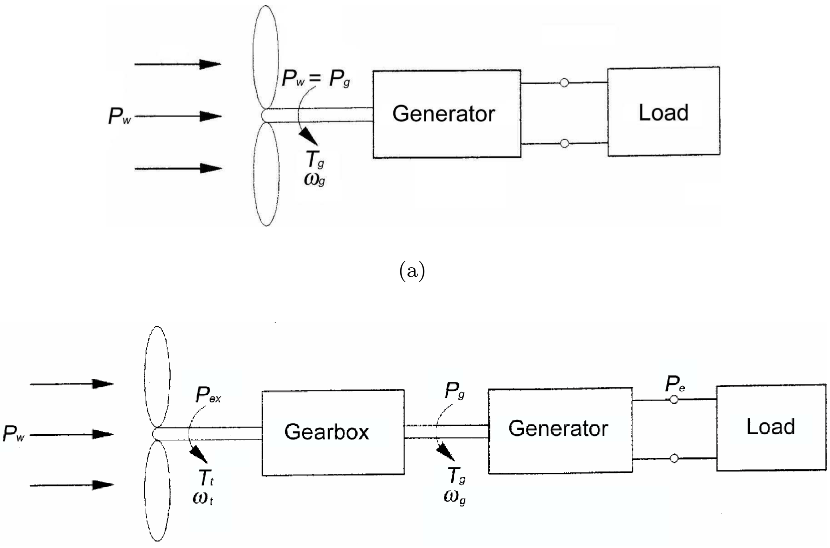
The solidity factor is defined as the total blade area of the rotor divided by the swept area normal to the wind. In a horizontal axis propeller machine, for example, an efficiently designed aerofoil intercepts a large area of wind with a small area of blade. It therefore has a low solidity factor, which is highly desirable.

Turbines with high solidity usually suffer from a large degree of aerodynamic interference between the blades which results in low values of both TSR and power coefficient. Examples are the Savonius rotor and the American farm multi-blade type, with the typical performance characteristic given in Fig. 10.14. Wind turbines of high solidity usually operate at low rotational speeds but have high starting torques. They are used for direct mechanical applications such as water pumping but are not suitable for driving electric generators. For the purpose of electricity generation it is usual to use low solidity machines such as the two-blade propeller in order to utilise high operational speeds and achieve high values of power coefficient.

10.5.5. *Shaft torque and power*

Most wind energy systems are used to generate electricity. The wind turbine is usually coupled to the electric generator directly, as in Fig. 10.15(a), or via a gearbox to step up the generator shaft speed, as in Fig. 10.15(b). For this reason the generator is invariably mounted at the top of the supporting tower, along with the turbine and gearbox. Electric cables run down the tower to connect the generator to its electrical load (e.g. lighting, electric motors, battery chargers) on the ground below. The wind as a power source is attractive because it does not impose an extra heat burden on the environment like the heat–work systems involving fossil or nuclear fuels. The torque, speed and power of a rotating shaft are linked by the relationship

$$P = T\omega \tag{10.22}$$



P_w = power in the wind
P_{ex} = power extracted
P_g = power into generator
P_e = electrical power generated
T_g = generator shaft torque
T_t = wind turbine shaft torque

ω_t = wind turbine shaft speed
ω_g = generator shaft speed

(b)

Fig. 10.15. Stages of wind-powered electricity generation: (a) direct-on load, (b) gearbox system.

If the power is in watts, then torque T is in Newton-metres (Nm) and the angular speed of rotation ω is in radians per sec. In Fig. 10.15 it follows that

$$T_t = \frac{P_{\mathrm{ex}}}{\omega_t} \tag{10.23}$$

and

$$T_g = \frac{P_g}{\omega_g} \tag{10.24}$$

Considerable torsional stress is imposed on the shaft due to the rotational forces on the turbine propeller. For a solid, cylindrical shaft, subjected to torque T, the torsional shear stress f_s at any arbitrary radius r, Fig. 10.16, is given by

$$f_s = \frac{Tr}{J}\ \mathrm{N/m^2} \tag{10.25}$$

where J is the polar (area) moment of inertia, having the dimension m^4. For a solid cylindrical shaft of radius r_0, J is given by

$$J = \frac{\pi r_0^4}{2}\, m^4 \tag{10.26}$$

Combining (10.25) and (10.26) gives an expression for the shear stress at the surface of a solid-cylindrical shaft of radius r_0

$$f_s = \frac{2T}{\pi r_0^3}\ \mathrm{N/m^2} \tag{10.27}$$

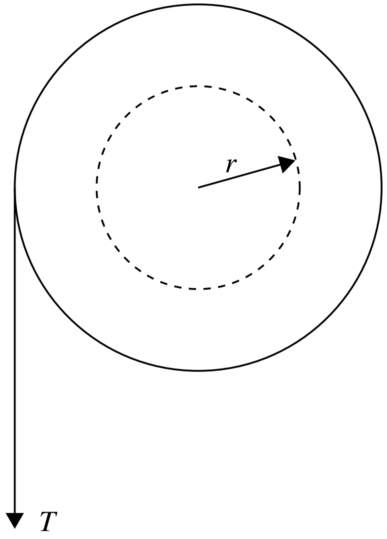


Fig. 10.16. Wind machine shaft.

10.6. Efficiency of Wind-Powered Electricity Generation

A power flow diagram indicating the principal components of the system is given in Fig. 10.17. The power ratios or efficiencies of the various stages in Fig. 10.17 are

$$\text{turbine efficiency} = \frac{P_{\text{ex}}}{P_w} = C_p \tag{10.28}$$

$$\text{gearbox efficiency} = \frac{P_g}{P_{\text{ex}}} = \eta_{gb} \tag{10.29}$$

$$\text{generator efficiency} = \frac{P_e}{P_g} = \eta_g \tag{10.30}$$

The overall efficiency of the three-stage system of Fig. 10.17 is

$$\eta = \frac{\text{electrical output power}}{\text{power available in the wind}} = \frac{P_e}{P_w} = \frac{P_{\text{ex}}}{P_w} \cdot \frac{P_g}{P_{\text{ex}}} \cdot \frac{P_e}{P_g} \tag{10.31}$$

Combining expressions (10.28)–(10.31) gives

$$\eta = \frac{P_e}{P_w} = C_p \cdot \eta_{gb} \cdot \eta_g \tag{10.32}$$

For small wind power installations, up to a few kW rating, the overall efficiency η is of the order 20–25%.

The electrical output power may be written as

$$P_e = C_p \cdot \eta_{gb} \cdot \eta_g \cdot P_w = C_p \cdot \eta_{gb} \cdot \eta_g \cdot \frac{1}{2}\rho A V^3 \tag{10.33}$$

For the two-blade propeller type of wind turbine

$$\begin{aligned} C_p &= 40\text{–}50\% && \text{for large machines (100 kW–3 MW)} \\ &= 20\text{–}40\% && \text{for small machines (1 kW–100 kW)} \\ &= 0.35 \text{ p.u.} && \text{typically for small machines} \end{aligned} \tag{10.34}$$

Modern types of mechanical gearbox have efficiencies that depend on the speed of rotation. At rated speed,

$$\begin{aligned} \eta_{gb} &= 80\text{–}95\% && \text{for large machines} \\ &= 70\text{–}80\% && \text{for small machines} \end{aligned} \tag{10.35}$$

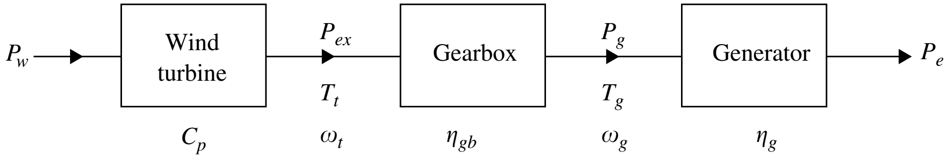


Fig. 10.17. Power flow in a wind converter system.

Electrical generators have efficiencies that increase with rated size. The process of converting rotational mechanical energy to electrical energy is inherently more efficient than any process involving heat to work (i.e. thermodynamic) conversion. For operation at rated speed

$$\begin{aligned} \eta_g &= 80\text{–}95\% \quad \text{for large machines} \\ &= 60\text{–}80\% \quad \text{for small machines} \end{aligned} \tag{10.36}$$

It is notable that large systems are more efficient than small systems. In general, an increase of scale is accompanied by an increase of efficiency.

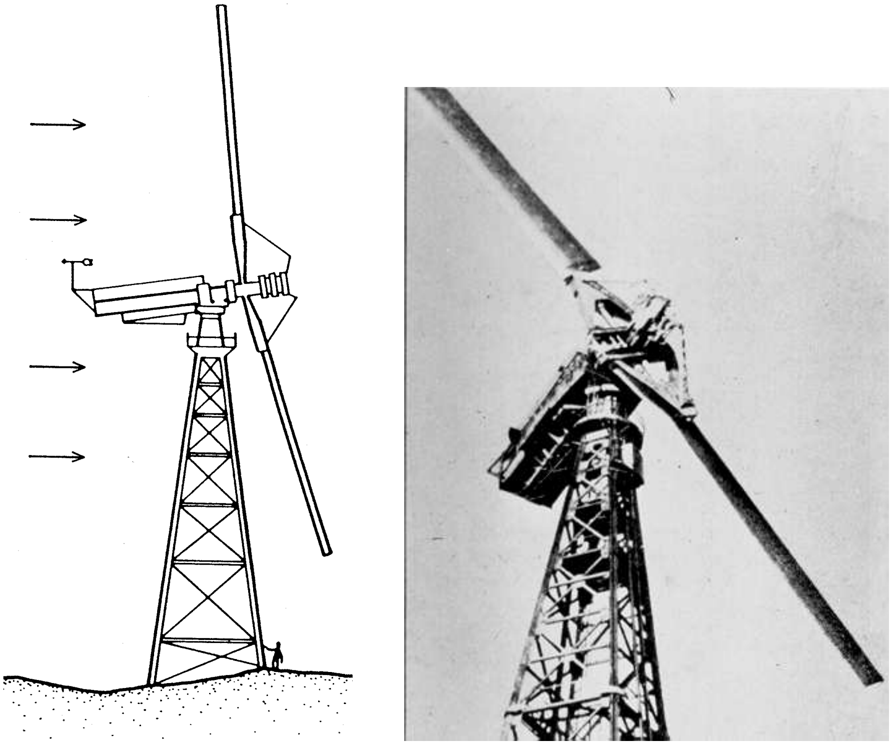
10.7. Large Wind Machine Systems

Various studies in Europe and the USA suggest that large wind machines are likely to be more economical to operate than small ones. But for both large-scale and small-scale operation, wind energy offers the hope of short-term, cost-effective electrical power generation. Present operation and planning is aimed towards machines with an electrical output in the range 1–5 MW. Many such systems are now (2002) in operation, all over the world.

10.7.1. *Historical background*

The first successful large wind turbine was the Smith–Putnam machine built at Grandpa's Knob, Vermont, USA, in the late 1930s [11]. This privately funded venture proved to be the prototype and inspiration for what has now become a vast industry. As with all horizontal axis propeller machines, the generator and gearbox were mounted on the turbine shaft in a housing at the top of the tower, Fig. 10.18. The Smith–Putnam machine was a two-blade propeller system, rated at 1.25 MW, with a blade diameter of 53.34 m (175 ft). For 35 years it held the record as the world's largest wind machine system. The electric generator was a synchronous machine that fed electrical power directly into the Central Vermont Public Service Corporation electricity grid.

The Smith–Putnam machine suffered two mechanical failures. After a main bearing replacement there was a spar failure causing one of the propeller blades to fly off. The operating company decided that a repair would be uneconomical and the venture was closed down in 1945. Although the Smith–Putnam machine operated only for 18 months in all, it was a proving ground for high-power wind power systems. The mechanical failures were due to limitations of knowledge of the materials available at the time and not to the basic system design. Better materials are now available. Also, engineering knowledge about bearing design and about the fatigue failure of metals make it unlikely that the Smith–Putnam type of failure would occur in modern wind turbines. Although the Smith–Putnam project was superficially a failure, it worked well for long enough to prove that large-scale,



(a) (b)

Fig. 10.18. Smith–Putnam wind machine [7]: (a) diagrammatic, (b) on-site photograph.

wind-powered electricity was feasible. All of the principal engineering challenges were overcome, opening the way to future development.

10.7.2. *Facing the wind — the yaw effect*

The wind at a given site is subject to rapid and frequent changes of direction. To maintain efficient operation the turbine propeller must remain perpendicular to the wind direction. This requires that the turbine-generator assembly be free to rotate about a vertical axis — a phenomenon that aeronautical engineers call the "yaw" effect. With good bearings, a machine can be easily pivoted to swivel under the influence of a vane mounted downwind. The rotating rudder-wheel in Fig. 10.1 serves the same purpose.

Control of the yawing forces can be obtained by mounting the propeller blades downwind, which was done in the Smith–Putnam machine, Fig. 10.18(a). The blades were slightly coned so that they swept out a broad cone rather than a flat circular area. In the Smith–Putnam machine, a weather vane monitored the wind direction and electric power was used to swivel the turbine-generator broadside on to the wind. This is similar, in principle, to power steering in a modern automobile.

It can be seen in Fig. 10.18(a) that the axis of the shaft is slightly tilted with respect to the horizontal. This was designed to accommodate the wind flow direction over the local ground contour.

10.7.3. *Centrifugal forces*

Rotation of the blades of a wind machine causes outward-acting centrifugal forces. This phenomenon can be experienced by tying a weight at the end of a string and swinging it around. The outward force depends directly on the mass or weight and on the speed of rotation. Calculation of the centrifugal forces, tending to pull the propeller blades out of their sockets, is complicated because the weight is distributed non-uniformly along the length of the blade. A simple calculation that assumed all the weight to be concentrated at a fixed radius of rotation would give wildly inaccurate results. In large modern wind machines the blades are large and heavy. Moreover the cost of the blades is a significant portion of the total system cost.

The amount of power taken from the wind at a fixed wind-speed can be adjusted by varying the pitch-angle of the propeller blades. This is realised by rotating the propeller arms in their sockets, like adjusting a screw or bolt. In effect, this changes the force and torque exerted on the rotating propeller. The same principle is used in landing a propeller-drawn aeroplane, to change the thrust on the blades and thereby reduce the speed. Use of the same technique enables the power extracted from a propeller to be kept constant over a range of wind speeds, as illustrated in Fig. 10.19. When the wind speed reaches a maximum acceptable level, known as the furling velocity V_f, the pitch-angle of the blades can be adjusted so that zero power is extracted. In severe wind conditions some form of mechanical brake is applied.

10.7.4. *Gyroscopic forces and vibrations*

A large wind turbine usually has its blades rotating about a horizontal axis, while the turbine-generator housing is free to rotate about a vertical axis. Yawing rotation about the vertical axis while the propeller is turning encounters strong gyroscopic forces. These forces have to be transmitted through the bearings and propeller shaft, causing high stresses and vibrations. For this reason the propeller blades should be made of a lightweight material such as a composite plastic like fiberglass rather than metal.

The act of rotation of the blades also results in periodic vibrations. With a downwind machine, as are many large designs, each blade passes through the wind shadow of the tower once per rotation. This results in a sudden reduction followed by a sudden increase of the air pressure upon it, which applies a bending moment force on each blade at its root or hub joint. The continued horizontal flexing of the propeller blades every rotation produces fatigue stress in the materials.

In order to minimise the vibration problem, some wind machine designers prefer to use three-blade propellers rather than two-blade propellers, even with the added cost of the extra blade.

10.7.5. *Modern large wind power installations*

The design, construction and operation of large (i.e. a few megawatts (MW) down to hundreds of kilowatts (kW)) wind turbine systems for electricity generation is now a well-established technology. Most large-scale systems use horizontal axis, two-blade propeller designs. Although the basic scientific and engineering problems have been solved, difficulties still remain arising from political, environmental and economic considerations.

A crisis in the price and world supply of oil from the Middle Eastern oil-producing countries (OPEC) occurred in the early 1970s. This was a great incentive to the industrialised countries of Western Europe and North America to investigate alternative supplies of energy. Since the early 1970s the USA, in particular, has made a massive investment of effort in the development of wind turbines and wind-powered electricity generation schemes. This has been organised via the US Electrical Research Development Association (ERDA).

In 1974 the ERDA Model Zero (MOD-0), 100 kW, machine was reported [12]. This was a two-blade, variable-pitch propeller, downstream turbine with diameter 38.1 m (125 ft). The AC synchronous generator was driven via a step-up gearbox and fed electrical power directly into the local grid. Subsequent MOD-0 machines were upgraded to 200 kW rating.

The MOD-1 wind turbine system was commissioned in 1979 and became, at the time, the world's largest machine. The MOD-1 was also a two-blade propeller, downwind machine, rated at 2 MW, with a blade diameter of 60.96 m (200 ft). This was followed in 1980 by the first MOD-2 machine, rated at 2.5 MW, with a blade diameter of 91 m (298.6 ft) and upstream orientation. A group of three MOD-2 machines, on a fixed site, with hub heights of 60 m and providing a test-bed for examining the effects of machine clustering, was operating in 1984. A MOD-5 programme involving two-blade, upwind machines rated at 7.3 MW, with a blade diameter of 122 m (400 ft), was planned for the late 1980s. This plan was abandoned, not for technical reasons but because the reduced price of oil and the reduced demand for electricity made it uneconomical [13].

Large wind machines have a cut-in speed V_c (Fig. 10.19) of about 10 mph and rotate at speeds up to about 100 rpm. For economic reasons large systems need to operate in locations where the average wind speed is $\geq$ 15 mph.

Wind turbine design and development in Europe is dominated by Denmark and Germany. During the l980s, work concentrated on turbines with ratings of several hundred kW. These are now being upscaled to 800–900 kW. The first generation of 1.5 MW machines in 1995–96 was a giant technological step forward. There are now (2002) over 1100 machines of this class in operation. One company announced plans to manufacture 700 machines of 1.5 MW rating during the year 2001.

A total of l496 turbines, of average size 1150 kW, were installed in Germany during 2000. New offshore wind farms have been commissioned recently (2001) in Sweden, Denmark and the UK. The farm at Middelgrunden, Denmark, shown in Fig. 10.20, is the largest in Europe at present.

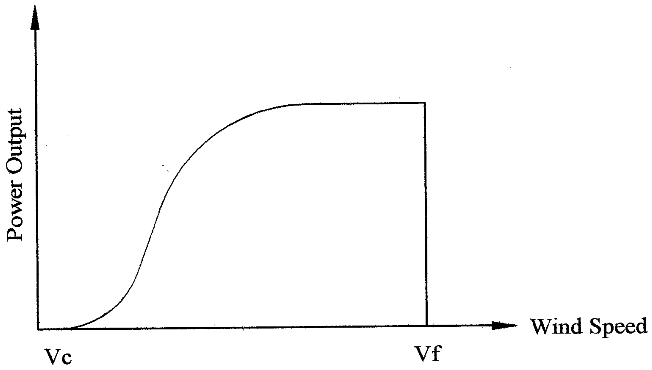


Fig. 10.19. Effect of feathering the propeller.
V_c = cut-in speed
V_f = furling speed

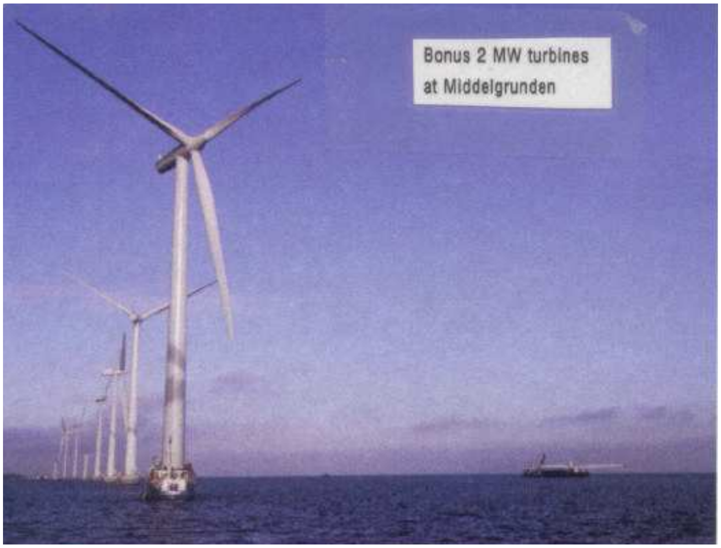


Fig. 10.20. Array of 2 MW offshore turbines at Middelgrunden, Denmark [14].

Offshore wind requires more reliable installations than onshore because they may not be accessible in rough weather. The next generation of offshore turbines are likely to be in the 3–5 MW range, with rotor diameters in excess of 100 m. Several manufacturers have announced commercial prototypes. The Vortec (trade name) offshore design shown in Fig. 10.21 is nominally rated at 5 MW [14].

Electricity generated offshore can be piped to shore using undersea cables and fed directly into the grid. Many examples of the undersea transfer of electrical power already exist. For example, nuclear-generated electricity is conducted from France to England by a cable under the English Channel. An alternative is to use the generated electrical power to electrolyse water into oxygen and hydrogen. Pressurised hydrogen would be transported to shore by pipelines. The hydrogen gas could be converted to electricity via a steam cycle, as is now done with natural gas.

Any offshore wind machine system has to be able to withstand the most severe weather to be encountered, including the "one in a 100 years superstorm".

In Great Britain many experimental onshore wind machines have been planned since the 1930s, but relatively few were built and tested. A 100 kW machine of elegant, streamlined design and appearance was built in the 1950s by the British Electricity Authority but it proved to be of unacceptably low efficiency. Also, there were local environmental objections to its proposed permanent location on the coast of North Wales. This machine has now been operating successfully in Algeria for 40 years [1].

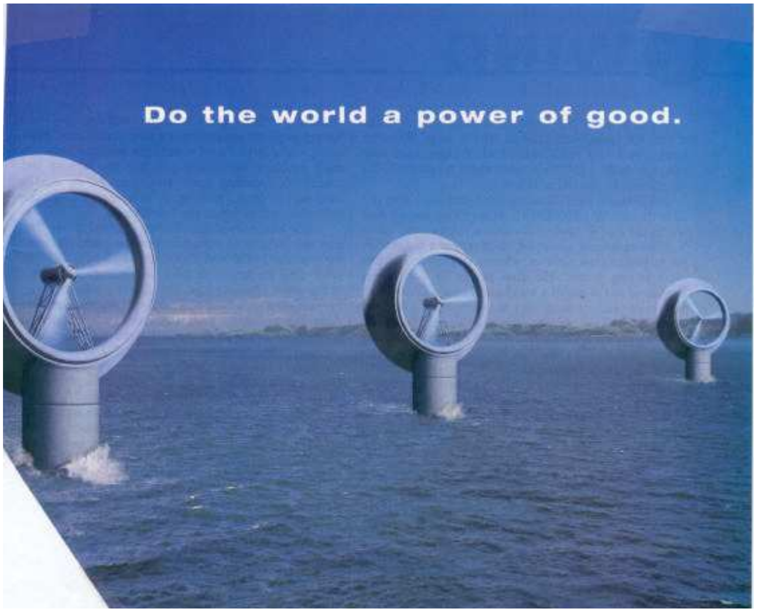


Fig. 10.21. Vortec offshore turbines [14].

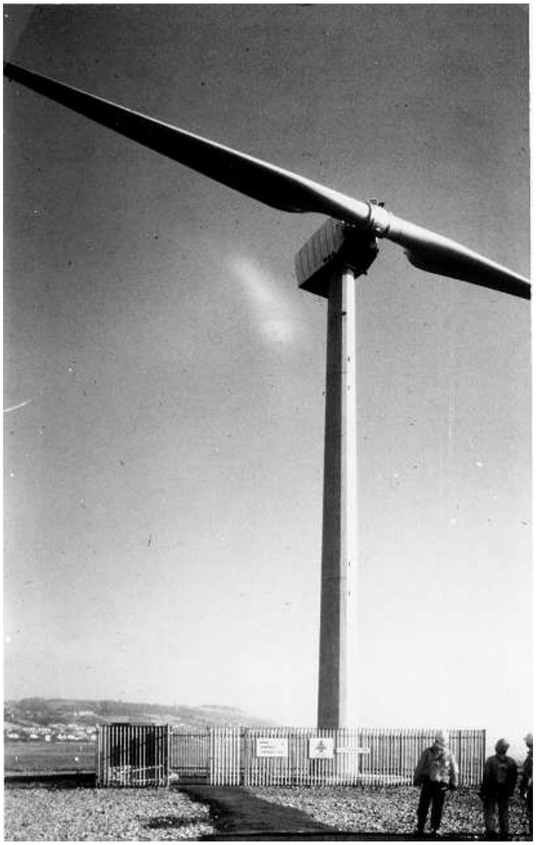
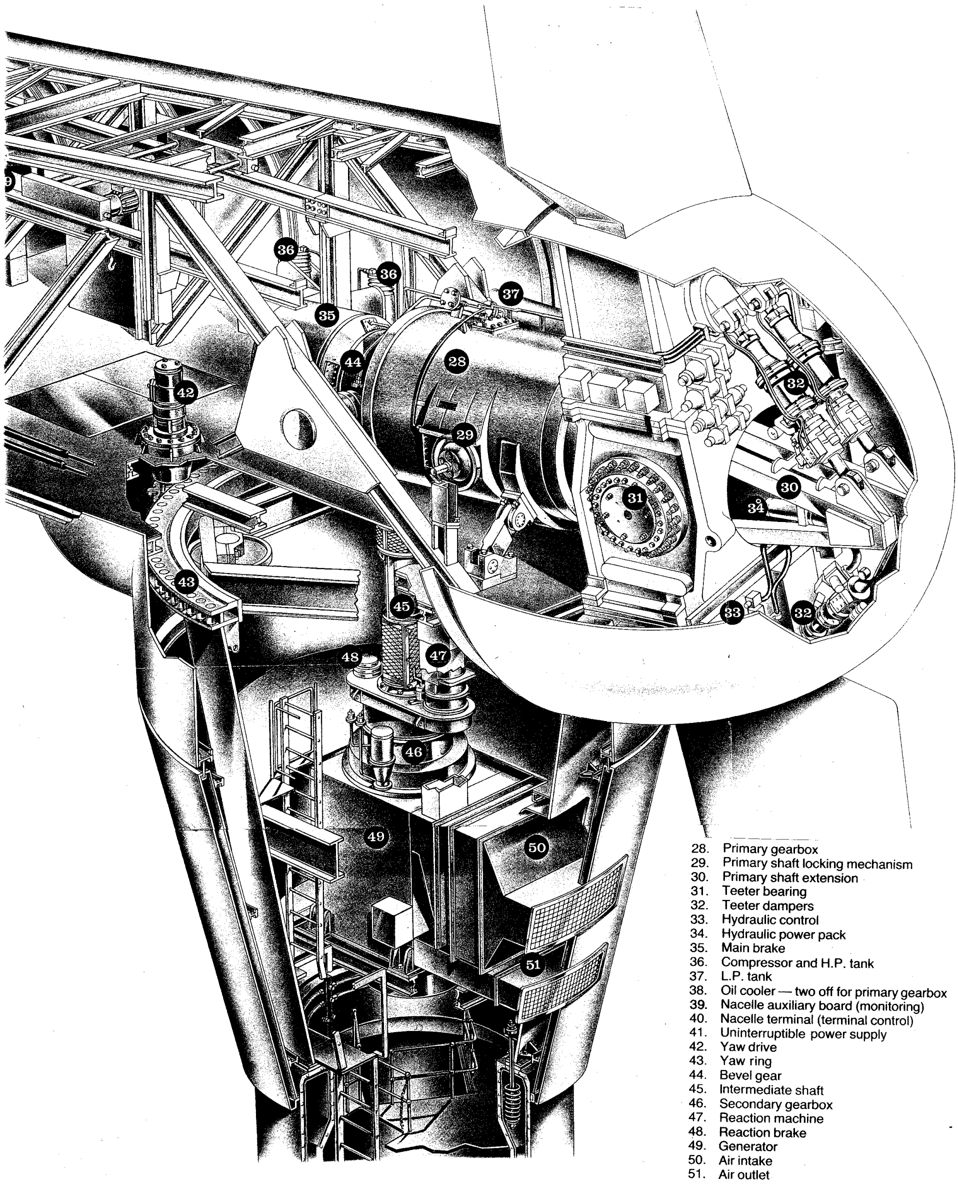


Fig. 10.22. 3 MW wind machine in Orkney, Scotland [15].

The largest wind turbine now (2002) operating, very successfully, in the British Isles is situated in Orkney. Located off the north coast of Scotland, the Orkney Islands are in one of the windiest locations in the world, with average wind speeds of the order 17 m/s ($17/0.447 = 38$ mph). The high wind speed permits the 3 MW upstream machine to use the relatively small blade diameter of 60 m (197 ft) at a hub height of 46 m (151 ft). Electrical power generated by the Orkney machine, Fig. 10.22, is used on the islands and replaces the expensive diesel-electric generation previously used [15]. An impression of the size and internal complexity can be gauged from the impression of Fig. 10.23 [16]. Wind speeds up to 60 mph can be utilised. The excessively windy location means that the machine is expected to generate more electrical energy (up to 9000 MWh/year) than any other known existing wind installation.

An assessment of the necessary scale of wind generation can be made by comparing the output power, 3 MW, of modern high efficiency turbines with a conventional large power station which produces 1000–2000 MW. To replace the electrical



28. Primary gearbox
29. Primary shaft locking mechanism
30. Primary shaft extension
31. Teeter bearing
32. Teeter dampers
33. Hydraulic control
34. Hydraulic power pack
35. Main brake
36. Compressor and H.P. tank
37. L.P. tank
38. Oil cooler — two off for primary gearbox
39. Nacelle auxiliary board (monitoring)
40. Nacelle terminal (terminal control)
41. Uninterruptible power supply
42. Yaw drive
43. Yaw ring
44. Bevel gear
45. Intermediate shaft
46. Secondary gearbox
47. Reaction machine
48. Reaction brake
49. Generator
50. Air intake
51. Air outlet

Fig. 10.23. Artistic impression of the internal construction of a 3 MW wind machine [16].

output power of a 1000 MW fossil fuel or nuclear station would require 333 Orkney size machines or 400 ERDA MOD-2 machines. To take account of the necessary spacing between large wind turbines in the same cluster (i.e. approximately 1500 ft for 3 MW machines), 1000 MW of generation could require as much as 500 square miles of ground site. This could create local ecological disruption and aesthetic objections. In the USA the necessary tracts of land are available in the area of the windy western Great Plains. In the much smaller countries of Western Europe land is scarcer, more expensive and in demand for other uses such as farming. The land area required for wind-generated electricity is several times larger than that required for the corresponding solar thermal generation, discussed in the following chapter.

In December 2001 plans were announced to build the world's largest wind farm off the west coast of Scotland. The inland part of the project is to use 250 turbines, of total rating 600 MW, on the Hebridean island of Lewis, exporting the electricity generated to England via a 350-mile undersea cable. This would produce about ten times the electricity of Britain's present (2002) largest wind power station. The second stage is to be a bigger, offshore site in the same area, rated at 2000 MW [17].

10.7.6. *Worked examples on wind turbine operation*

Example 10.1

Use the data of Fig. 10.11 to predict the approximate diameter, in feet, of a windstream of circular cross-section that contains an extractable power of 1 MW in a wind speed of 38 mph, $C_p = 0.4$.

The 1 MW coordinate in Fig. 10.11 intersects the line representing 15 m/s (33.6 mph) at a cross-sectional area of approximately 1100 m^2. Interpolating between coordinates on a non-graduated logarithmic scale is necessarily a "rough and ready" procedure. The value 38 is almost midway between the calibrated characteristic parameters of 44.74 and 33.6 in Fig. 10.11 but the 38 mph characteristic does not lie midway between the two calibrated characteristics.

By estimation, 1 MW extractable power, at 38 mph, corresponds to a wind stream area of 1000 m^2.

$$\begin{aligned} A &= 1000\ \text{m}^2 \\ &= 1000 \times \left(\frac{39.37}{12}\right)^2 \\ &= 10764\ \text{ft}^2 \\ \text{But } A &= \frac{\pi D^2}{4} \\ \therefore\ D^2 &= \frac{4 \times 10764}{\pi} = 12732\ \text{ft}^2 \\ D &\fallingdotseq 112.84\ \text{ft} \end{aligned}$$

Example 10.2

The largest wind turbine in the British Isles to date (2002) is the 3 MW generator system in the Orkney Isles, north of Scotland. Use the data of Fig. 10.11 to roughly verify its swept diameter for operation in a 38 mph wind.

The Orkney wind generator system is rated at 3 MW electrical output power. To realise this the extractable power from the wind P_{ex} would need to be (say) 20% or 3.75 MW bigger. Interpolating between the 1 MW and 10 MW gradations in Fig. 10.11, for 3.75 MW, is about a half way and corresponds to a horizontal intercept of roughly $A = 3000\ \text{m}^2$. The actual design diameter of the Orkney machine is 60 m, giving a swept area

$$A = \frac{\pi D^2}{4} = \frac{\pi}{4} \cdot 3600 = 2827.4\ \text{m}^2$$

Despite the limitations of reading from a small-scale logarithmic data sheet, it can be seen that there is good correlation.

Example 10.3

A wind turbine of the two-blade propeller type is designed to have its maximum power coefficient value at a tip-speed ratio, TSR = 6, when the wind velocity is 25 mph. If the blade diameter is 100 ft, what is the recommended speed of rotation?

$$V = 25\ \text{mph} = 25 \times 0.447 = 11.18\ \text{m/s}$$

From (10.20),

With TSR = 6

$$\begin{aligned} v &= r\omega = V \times \text{TSR} = 6 \times 11.18 = 67.1\ \text{m/s} \\ D &= 100\ \text{ft} = 100 \times 12/39.37 = 30.5\ \text{m} \\ r &= D/2 = 15.25\ \text{m} \end{aligned}$$

Speed of rotation

$$\omega = v/r = 67.1/15.25 = 4.4\ \text{rad/s}$$

From (10.21),

$$n = 60\omega/2\pi = 42\ \text{rpm}$$

Example 10.4

Evaluate typical values of overall working efficiency for (a) large wind machine systems, and (b) small wind machine systems, assuming realistic values of the various stage efficiencies.

(a) For large wind turbine systems, typical stage efficiencies are:

$$\begin{aligned} &\text{from (10.34)}, \quad C_p = 0.42 \\ &\text{from (10.35)}, \quad \eta_{gb} = 0.85 \\ &\text{from (10.36)}, \quad \eta_g = 0.92 \end{aligned}$$

Then from (10.32), $\eta = 0.42 \times 0.85 \times 0.92 = 33\%$

(b) For small wind turbine systems, typical stage efficiencies are

$$\begin{aligned}
&\text{from (10.34)}, \quad && C_p = 0.3 \\
&\text{from (10.35)}, \quad && \eta_{gb} = 0.75 \\
&\text{from (10.36)}, \quad && \eta_g = 0.7 \\
&\text{from (10.32)}, \quad && \eta = 0.3 \times 0.75 \times 0.7 = 16\%
\end{aligned}$$

There is seen to be an overall efficiency advantage of the order 2:1 in using large-scale wind generation.

Example 10.5

Wind turbine units are rated at 2 MW in a rated wind speed of 13 m/s. The stage efficiencies are $C_p = 0.32$, $\eta_{gb} = 0.94$, $\eta_g = 0.96$. What is the necessary swept area? If the rotor is a two-blade propeller (horizontal axis), what is the rotor diameter? ($\rho = 1.29$ kg/m^3.)

$$\begin{aligned}
\eta &= 0.32 \times 0.94 \times 0.96 = 0.29 \\
P_e &= 2 \text{ MW} \\
\therefore\ P_w &= \frac{P_e}{\eta} = \frac{2 \times 10^6}{0.29} = 6.9 \times 10^6 \text{ W}
\end{aligned}$$

Now

$$\begin{aligned}
P_w &= \frac{1}{2}\rho A V^3 \\
6.9 \times 10^6 &= \frac{1}{2} \times 1.29 \times A \times (13)^3 \\
A &= \frac{2 \times 6.9 \times 10^6}{1.29 \times (13)^3} = 4870 \text{ m}^2
\end{aligned}$$

For a circular area

$$A = \frac{\pi D^2}{4}, \quad D = 78.8 \text{ m (258 ft)}$$

The comparatively large diameter is because of the low value of the turbine power coefficient.

Example 10.6

A generator driven by a wind turbine is required to deliver 1.5 MW of power at the generator terminals. The turbine rotor is a two-blade propeller rotating about a horizontal axis and the maximum permitted shear stress of the turbine shaft is 55×10^6 N/m^2. The rotor is designed to operate at a fixed rotational speed of 22 rpm.

(a) If the turbine delivers its rated power at a wind average speed of 25 mph, calculate the corresponding diameter of the propeller and its tip-speed ratio, assuming a typical value for the overall efficiency. The air density may be assumed to have a value 1.29 kg/m^3.

(b) Calculate the torque on the turbine shaft and the shaft diameter.

$$\text{(a)}\quad P_{\text{elect}} = 1.5\text{ MW}$$

$$\text{Let } \eta = 0.3 \text{ overall}$$

$$\therefore\ P_{\text{wind}} = \frac{P_{\text{elect}}}{\eta} = \frac{1.5\times10^6}{0.3} = 5\times10^6\text{ W}$$

$$\text{Now } 25\text{ mph} \equiv 11.175\text{ m/s}$$

$$\text{But wind power } P_{\text{wind}} = \frac{1}{2}\rho A V^3$$

$$\therefore\ A = \frac{2\times5\times10^6}{1.29\times(11.175)^3} = 5555\text{ m}^2$$

$$\text{But } A = \frac{\pi D^2}{4}$$

$$\therefore\ D = \sqrt{\frac{4\times5555}{\pi}} = \sqrt{7073} = 84.1\text{ m (275.9 ft)}$$

$$\text{Tip-speed ratio (TSR)} = \frac{r\cdot\omega}{V}$$

$$r = \frac{D}{2} = 42.05\text{ m}$$

$$\omega = 22\times\frac{2\pi}{60} = 2.3\text{ rad/s}$$

$$\therefore\ \text{TSR} = \frac{42.05\times2.3}{11.175} = 8.65$$

$$\text{(b)}\quad T = \frac{P}{\omega} = \frac{5\times10^6}{2.3} = 2.174\times10^6\text{ Nm}$$

$$\text{Now stress } f_s = \frac{Tr}{J} = \frac{Tr}{\frac{\pi r^4}{2}} = \frac{2T}{\pi r^3}$$

$$\therefore\ r^3 = \frac{2T}{\pi f_s} = \frac{2\times2.174\times10^6}{\pi\times55\times10^6} = 0.02516\text{ m}^3$$

$$\therefore\ r^3 = \frac{25.16}{1000}$$

$$r = \frac{\sqrt[3]{25.16}}{10}$$

$$\therefore r = \frac{2.93}{10} = 0.293 \text{ m}$$

$$= 29.3 \text{ cm (11.53 inches)}$$

by trial and error

$$2.8^3 = 21.9$$

$$2.9^3 = 24.4$$

$$2.92^3 = 24.9$$

$$2.93^3 = 25.15$$

Example 10.7

The Orkney wind machine is rated at 3 MW, at the rated wind speed of 17 m/s, with a blade diameter of 60 m. What is the power coefficient of the turbine? ($\rho = 1.29$ kg/m^3.)

From (10.6),

$$\begin{aligned} P_w &= \frac{1}{2}\rho A V^3 \\ &= \frac{1}{2} \times 1.29 \times \frac{\pi(60)^2}{4} \times 17^3 \\ &= 8959810 \text{ W} \\ P_e &= 3 \text{ MW} \end{aligned}$$

Overall efficiency is then, from (10.32),

$$\eta = \frac{3 \times 10^6}{8959810} = 0.335 \text{ p.u.}$$

But $\eta = C_p \cdot \eta_{gb} \cdot \eta_g$.

If $\eta_{gb} = 0.90$ and $\eta_g = 0.90$ the turbine power coefficient is

$$C_p = \frac{0.335}{0.9 \times 0.9} = 0.414$$

Example 10.8

A report by the Electrical Research Association of England suggests that there are about 1500 UK land-based sites, having wind speeds of 20 mph, suitable for wind turbine-generator systems [18]. What portion of the 2000 UK demand for electricity could be supplied?

Assume that one could mount one 3 MW turbine or three 1 MW turbines in each location. If all of the turbines in all the locations were working to capacity at the same time — an unlikely eventuality — the total power available would be

$$P_{\text{total}} = 3 \times 1500 = 4500 \text{ MW}$$

This is equivalent to the power output of four or five medium–large power stations. There are 8760 hours/year. If all of the wind systems operated to capacity for 24 hrs/day and 365 days/year, the energy produced would be

$$W_{\text{ideal}} = 365 \times 24 \times 4500 = 39.42 \times 10^6 \text{ MWh/yr}$$

If one includes consideration of down-time for repair and maintenance and also periods of slack wind, then about one half of this might be available,

$$W_{\text{avail}} \approx 20 \times 10^6 \text{ MWh/yr} \approx 20 \text{ TWh/yr}$$

In 2000 the total UK electricity consumption was 338.5 TWh [19]. The reported wind supply would therefore contribute 20/338.5 or 5.9% of the demand.

10.8. Vertical Axis Wind Machines

Most of the earliest historical accounts of wind machines refer to vertical axis structures used for pumping water. Small vertical axis machines with rotating vanes or rotating cups are now very widely used for instrumentation purposes, such as wind measurement. Currently much research is being devoted to vertical axis wind turbine systems for electricity generation, especially in the low and medium power ranges (a few tens of watts up to tens of kilowatts). The effective moving rotor surfaces move in the wind direction, rather than perpendicular to it. It is a feature of vertical axis machines that they accept the wind forces equally well from any direction. The issues of upstream, downstream, tower shadow and yaw that occur in horizontal axis propellers do not arise. Orientation of the blades into the wind is not required. Turbine power coefficients tend to be low — usually less than 1/3, which is the theoretical maximum. With a vertical axis machine the electric generator can be mounted on the ground at the bottom of the shaft.

10.8.1. *The Savonius design*

The most basic of the modern types of vertical axis wind turbines is the Savonius rotor, Fig. 10.24. This consists of a hollow cylinder that is cut along its long axis to form two semi-cylinders. The two halves are mounted into a rough "S" shape so that the wind flows through the cavity, being directed from the back of the concave side onto the inside of the convex side, resulting in rotation [2].

Savonius wind machines have a low cut-in speed and can operate in winds as low as 5 mph. This makes the machine suitable for electricity generation in low power

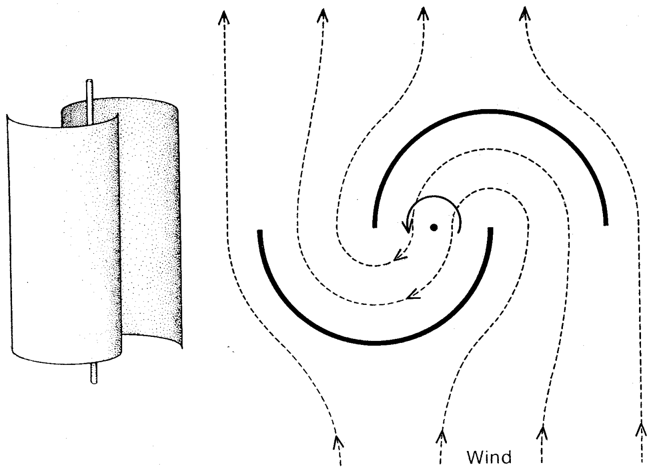


Fig. 10.24. Savonius rotor and its air-stream flow [2].

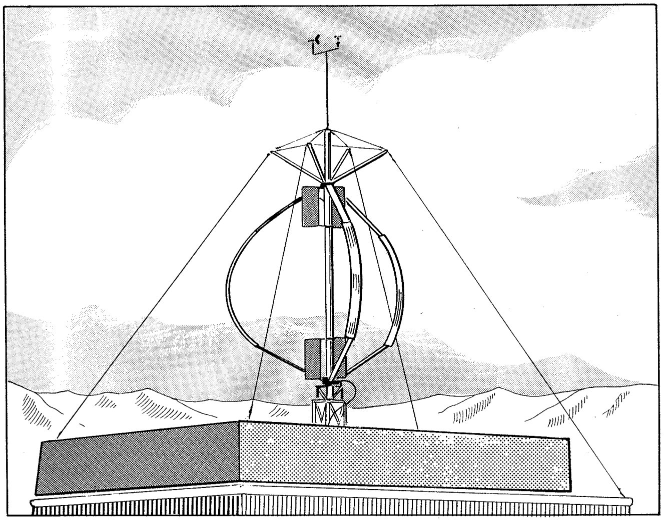


Fig. 10.25. Darrieus rotor [19].

applications such as individual domestic installations. The machine is particularly suited to locations of variable wind direction. A Swiss company markets a 6 kW version of the Savonius machine. The peak efficiency of this form of turbine is about 30% (Fig. 10.14) and the tip-speed ratio is low.

A disadvantage of the Savonius design is its high solidity factor. Also, the machine is heavy if metal vanes are used. Because of the nature of the construction the vane or sail area cannot be modified, so that the machine may need to be tied stationary in high winds.

10.8.2. *The Darrieus design*

Much attention and research effort has been devoted to the Darrieus wind machine. This looks like an egg-beater or food-mixer and consists of two or three vertically mounted vanes with aerofoil cross-sections [20]. The shape of the vanes, Fig. 10.25, is the natural shape that a flexible cable, like a skipping rope, would adopt if it was swung horizontally about the bottom and top pivots.

Unlike the Savonius rotor, the Darrieus machine is not self-starting. The fixed pitch rotor must be in rotation before the wind exerts a driving force on it. In practical designs a Savonius rotor is often incorporated onto the Darrieus shaft to provide a starting torque. At high speeds a Darrieus machine produces far more power than a Savonius machine and has a much higher tip-speed ratio, Fig. 10.14.

Darrieus machines have been studied for single-dwelling domestic housing applications. A blade diameter of about 15 ft is needed to produce 1 kW of output power. The Darrieus design has a peak efficiency of about 35%. A government-sponsored, large-scale Darrieus turbine was developed at the Sandia National Laboratories, Albuquerque, New Mexico, USA in the early 1980s. This used a blade diameter of 55 ft to develop a power of 80 kW. Another three-blade Darrieus machine in the USA had developed 500 kW. The world's largest Darrieus project, in Quebec, Canada, has developed a 4 MW machine. This is comparable in rating with the largest horizontal axis propeller systems.

As an alternative to Savonius assisted start-up, a Darrieus system can be started by using its coupled generator as a starter-motor, taking electrical power from the battery or electricity supply.

Darrieus machines have a low solidity factor, comparable with that of a horizontal axis propeller system, which makes for an economical use of aerofoil materials. The centrifugal forces of rotation exert tensile stresses on the blades, which may be metallic or made of fibreglass. The forces on the blades are similar in some respects to the aerodynamic forces on an aeroplane wing section or aerofoil.

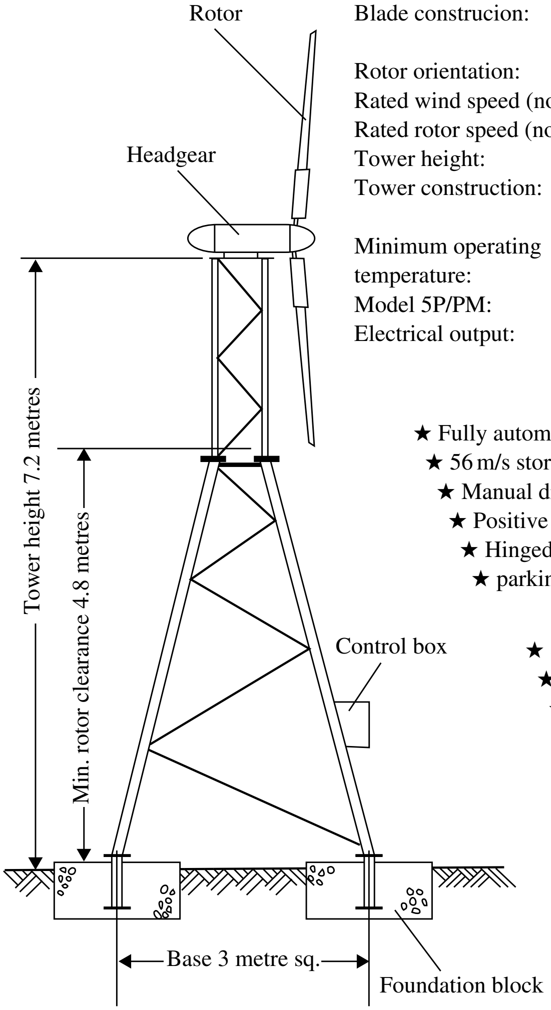
It should be noted that the detailed operation of both the Savonius and Darrieus design is very complex. Analyses cannot be undertaken using the comparatively simple equations of Sec. 10.5.

10.8.3. *Other forms of vertical axis machine*

There are many different forms of modern vertical axis machine. The most promising of these are derivations of the Darrieus principle. For example, Musgrove has designed machines with rotors of a two-blade or three-blade "H" configuration. Two vertical blades can either use a fixed tilt angle with rigid fixing to the hub or be hinged for variable tilt angles. At high speeds the variable tilt blades move outwards due to centrifugal action and act to govern the speed of rotation, eliminating the danger of overspeeding [21].

10.9. Small and Medium Size Machines

The principal form of future wind-powered electricity generation is likely to be by means of large machines of several megawatts rating, located far from the consumers that they supply. But, in addition, the use of small systems rated at several hundreds of watts or a few kilowatts is gaining popularity for domestic and for small



Technical Specification

Rotor diameter:	5 metres
No. of blades:	2
Furling method:	Torsion flexure
Blade construcion:	Aerofoil section glass resin bonded fibre envelope on steel structural spar
Rotor orientation:	Downwind
Rated wind speed (nom.):	13.4 m/s
Rated rotor speed (nom.):	435 rpm
Tower height:	7.2 metres
Tower construction:	Square section tubular steel lattice
Minimum operating temperature:	
Model 5P/PM:	–5 °C
Electrical output:	Nominally 7.5 kW 240 Vac 50 Hz three-phase at rated wind speed

Features

★ Fully automatic blade furling
★ 56 m/s storm survival
★ Manual dis-orientation
★ Positive locking of stationary rotor
★ Hinged tower base
★ parking brake

Applications

★ Space heating
★ Water heating
★ Soil heating
★ Battery charging
★ Remote region power supplies

Options

Electrical options include:
(i) Priority load controller
(ii) 220 V & 380 V, 3-phase alternator outputs
(iii) Economy & professional (500 w) battery chargers
(iv) Low temperature spec. (–20 °C)

Fig. 10.26. Scale of small wind system for electricity generation (unknown commercial origin).

business and commercial use. Economic operation of small wind-powered generators requires average wind speeds of 12 mph, being rather less stringent than for large systems.

The scale of machine needed to raise 7.5 kW of electrical power in a 13.4 m/s (30 mph) wind, for example, is shown in the commercial diagram of Fig. 10.26. A structure with a hub height of almost 24 ft and a rotor diameter of 16.4 ft would obviously be suitable only on a property with ample land area such as a farm, for example, or on a remote hilltop site in suburbia. It is much too large and obtrusive for an urban residential area.

To obtain even a few hundred watts of delivered electrical power requires a wind turbine several feet in diameter, as indicated in the data of Table 10.2 for ideal operation. A good example is the multi-blade American farm windmill in which a rotor of 4–5 ft diameter provides a few hundred watts of lighting or water pumping power for farm buildings. Such machines have a very high solidity factor and low efficiency, Fig. 10.14, but are useful sources of free power. They can be turned edgeways to the wind when not required to operate.

An essential requirement for the use of a wind machine system is sufficient land area at the site. For even a small turbine the location must be clear of wind obstructions such as buildings and will therefore be highly visible, well above ground level. In Britain it might be difficult to obtain planning permission from the appropriate Local Authority, even if the proposed site is fairly remote from other residences or buildings. Blade failure would likely result in total destruction of the installation as well as being dangerous to bystanders. The acoustic noise of the rotor blades and gearbox might be offensive. Rotation of the blades could cause electromagnetic noise and television interference, especially if metal blades are used. These disadvantages have to be set against the enormous advantage of a source of free, infinitely renewable and non-polluting fuel.

10.10. Electrical Engineering Aspects of Wind-Generated Electrical Power

10.10.1. *Electricity generator systems*

Most public electricity supply systems are of a three-phase, alternating current (AC) nature, with fixed values of frequency and voltage. The waveform of the supply voltage is sinusoidal. An electrical power system is capable of storing much electrical energy. This is an essential requirement where a wind generator feeds a power system but there may be no immediate direct load.

The generators used in wind turbine systems may be of a direct current (DC) nature or of an alternating current (AC) nature. Large installations invariably use AC generation, which can take one of two forms. Synchronous generators, or alternators, require a DC winding or permanent magnet field excitation and deliver a voltage and frequency proportional to the speed of rotation. Induction generators use AC field excitation and the frequency of the generated voltages depends both on the frequency of the excitation voltages and on the speed. The European market leaders in large wind turbines have recently (2002) started to develop doubly fed, wound-rotor induction machines and have already fitted a 2 MW system [14].

If the load on the generator is resistive, such as for lighting or heating, this can be supplied directly from the generator terminals or via a controlled rectifier [Figs. 10.27(a) and (b)]. The charging of a DC lead-acid storage battery can also be realised using a controlled rectifier to adjust the charging voltage to 6 V, 12 V or 24 V, as required. A useful resistive load application is to pass current through an electric immersion heating coil in a solar water heating system, as in Fig. 11.17 of Chapter 11. Water is a good storage medium and combination wind energy/solar energy systems are useful to supplement each other.

Another option is to couple the generator output directly to the terminals of a three-phase induction motor, Fig. 10.27(c). An induction motor can operate over a wide range of voltage and frequency. A pump application is suited to the intermittent nature of the incoming energy.

For the purpose of wind-powered electricity generation, the generated power usually has to be fed into an electricity grid system of frequency 50 Hz or 60 Hz. The wind, however, is variable in speed, strength and direction. An electrical system that transfers energy from a variable-speed prime mover to a constant frequency electrical system is called a variable-speed constant frequency (VSCF) system. A corresponding application arises in aircraft electrical generator systems where the aircraft operates at a constant frequency of 400 Hz but the engines driving the generators vary from idling speed to full-throttle speed (a speed range ratio of 1:5, or more).

Several options for VCSF systems are given in Figs. 10.27(d)–(f). The most widely used method, Fig. 10.27(e), utilises a controlled rectifier to produce direct current which is then inverted to line frequency alternating current and injected into the electricity grid.

10.10.2. *Small electrical generators*

Wind turbines usually operate at low speeds, up to 100 rpm. In some systems the blade pitch is automatically controlled to maintain constant rotational speed in the presence of variable wind speed. Electricity generators, both AC and DC, are often designed to operate at much higher speeds, of hundreds and even thousands of rpm. (Note: exceptions are the vast water-powered turbine-generator systems used in hydroelectric schemes, Chapter 9.) The terminal voltage V of an electric generator can be represented by the relationship

$$V = K\Phi N \tag{10.37}$$

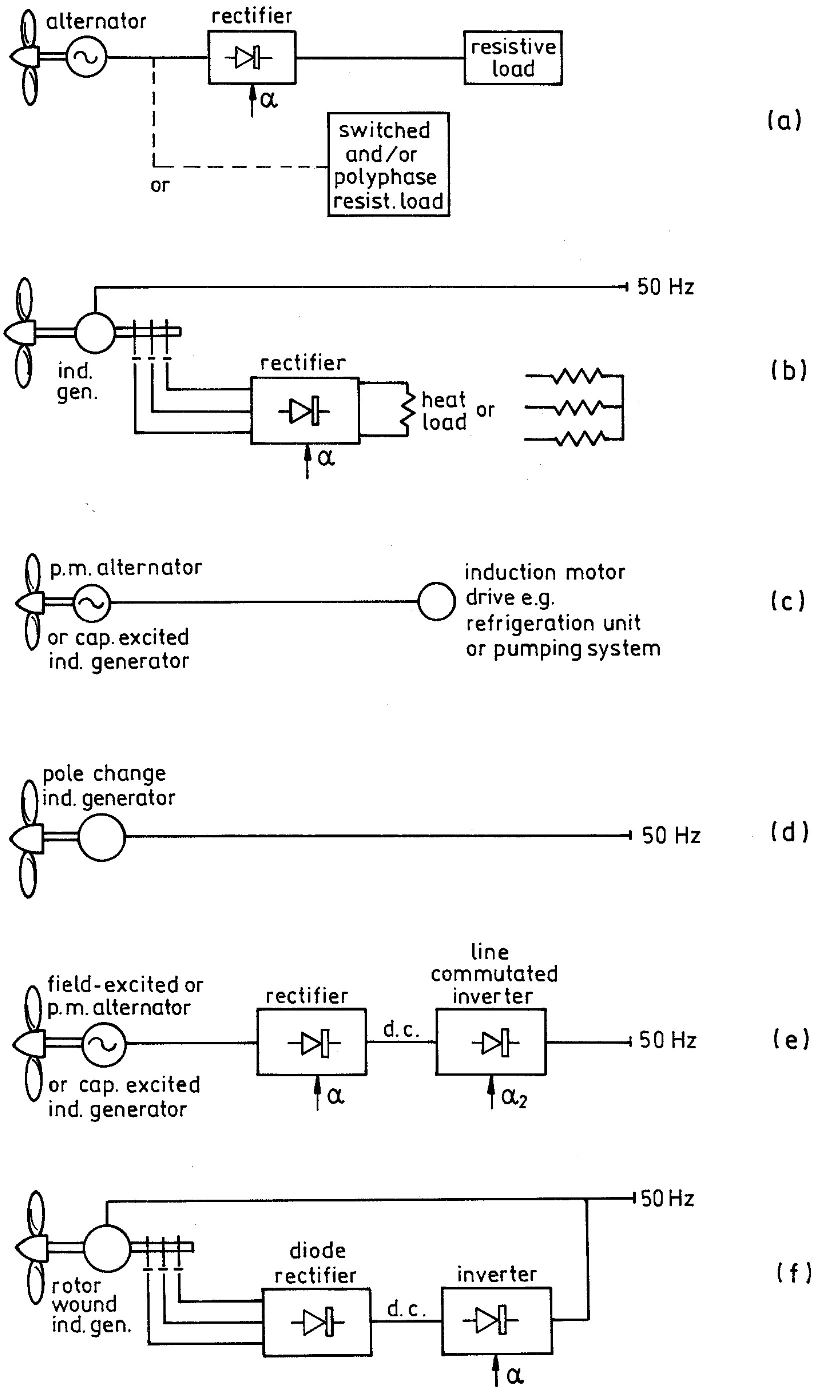

alternator
rectifier
α
resistive load
or
switched and/or polyphase resist. load
(a)
50 Hz
ind. gen.
rectifier
α
heat load
or
(b)
p.m. alternator
or cap. excited ind. generator
induction motor drive e.g. refrigeration unit or pumping system
(c)
pole change ind. generator
50 Hz
(d)
field-excited or p.m. alternator
or cap. excited ind. generator
rectifier
α
d.c.
line commutated inverter
α_2
50 Hz
(e)
50 Hz
rotor wound ind. gen.
diode rectifier
d.c.
inverter
α
(f)

Fig. 10.27. Electrical utilisation of wind-generated power: (a) synchronous generator with R load, (b) induction generator with R load, (c) direct AC motor drive, (d), (e) and (f) VSCF systems.

where

K = design constant, including the number of magnetic poles

Φ = magnetic flux per pole

N = shaft speed

If the speed N is small, then one needs a large magnetic flux, or a large number of poles, or both in order to maintain high voltage. It is possible to use high energy permanent magnets in small generators but these are costly. Similarly, it is possible to use multi-pole structures but these also are expensive to fabricate.

Low voltage systems can be used but suffer from an inherent disadvantage. The power demand of an electrical load varies directly with the product of voltage and current. If a low voltage is used then high current is needed to supply the necessary load power. High current circuits require large area, expensive cabling and also suffer from high losses because the resistance (heat) loss in the conductors is proportional to the current squared.

A common feature of wind energy systems is to use a gearbox to step up the generator shaft speed. A gear ratio of 10 or 20:1 may be needed. Gearboxes are precision pieces of engineering systems and are consequently expensive — a gearbox represents a significant portion of the first cost of a wind turbine-generator system. The gearbox is of the same order of weight and bulk as the generator. It has to be mounted adjacent to the generator, on top of the turbine tower, and the supporting structure has to be correspondingly strong.

10.11. Wind Machine Site Selection

The principal objective in wind turbine site selection is to obtain a high incidence of wind at a high wind speed. Relevant factors to be taken into account include:

(a) Geographical location
- access by road
- proximity to the nearest public electricity network

(b) Precise geographical position
- altitude
- proximity to other wind machines
- hilltop site

(c) Exposure
- screening of surrounding features such as hills, buildings, trees, etc.

(d) Shape of ground contours
- aerofoil effect of hills to enhance the wind velocity

(e) Seasonal variations of the wind
- contours of mean wind speed
- wind power/hours chart

(f) Direction of the prevailing winds
  - incidence of gusting
  - prevalence of windstorms

(g) Necessary height of the tower

(h) Acceptability to the environmentalist lobby
  - is the land still suitable for animal grazing?
  - does it mar sites of natural beauty?

(i) Costs
  - installation
  - repair and maintenance
  - on-site guarding
  - comparative costs of other power sources

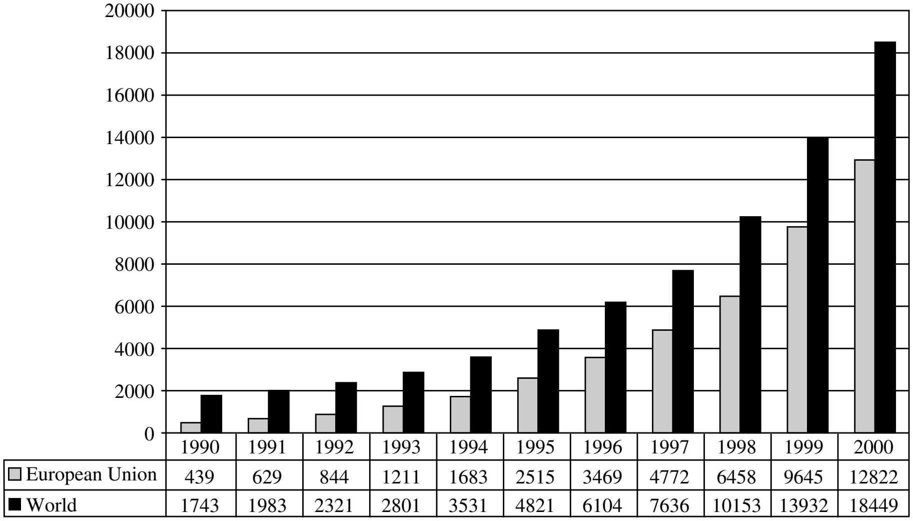
10.12. Pros and Cons of Wind-Generated Electrical Power

Some advantages and disadvantages of the use of wind power are summarised in Table 10.5, for convenience of reference. There is no clear-cut and explicit overriding feature which dominates the issue, above all others. Moreover, the weight that one might care to give to particular items in a table may be subject to national and international political considerations, which tend to change.

Continual improvements are being made in materials, design, fabrication and control systems for large wind turbines. "Farms" of large wind machines are now capable of generating electricity for 4 cents/kWh in regions of high wind density in the USA. This is slightly greater than one half the cost of conventional generation.

Table 10.5. Advantages and disadvantages of wind-powered electricity generation.

Advantages	Disadvantages
prime fuel is free	risk of blade failure (total destruction of the installation)
infinitely renewable	suitable small generators not readily available
non-polluting	unsuitable for urban areas
in UK the seasonal variation matches electricity demand	cost of storage battery or mains converter system
big generators can be located on remote sites, including offshore	acoustic noise of gearbox and rotor blades
saves conventional fuels	construction costs of the supporting tower and access roads
saves the building of (otherwise necessary) conventional generation	electromagnetic interference if metal rotor used
diversity in the methods of electricity generation	environmental objections



	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
□ European Union	439	629	844	1211	1683	2515	3469	4772	6458	9645	12822
■ World	1743	1983	2321	2801	3531	4821	6104	7636	10153	13932	18449

Fig. 10.28. Cumulative wind capacity in MW, 1990–2000 [23].

In 1994 there were estimated to be more than 25,000 wind turbines in operation worldwide [22]. The estimated global capacity of wind power facilities in 2001 was 18,449 MW supplying 37 TWh (37 billion kWh) per year [23]. Since 1990 the significant growth of wind generation capacity has been dominated by Europe, Fig. 10.28 [22]. The forecast is for a spectacular increase in the period 2001–2005 to more than three times the 2000 figure, as shown in Table 10.6 [23].

All financial features of the use of wind energy for electricity generation have to be considered in comparison with other options, in particular the price of oil. Comparative costings are published from time to time but there is no ongoing agreement as to the findings. This is to be expected because the perspective is influenced by personal as well as business and political considerations.

10.13. Problems and Review Questions

10.1. Sketch the form of the month-by-month variation of the wind power flux in the UK. Correlate this with the data of national electricity demand from Fig. 3.7 of Chapter 3. What conclusions may be drawn?

10.2. Use the information in Eq. (10.13) to show that maximum power is extracted from a windstream when the upstream velocity V_1 is three times the downstream velocity V_2.

10.3. If the wind speed in a certain location is doubled, how does this affect the power output of a wind generator?

Table 10.6. Forecast for global wind power development, 2001–2005 [23].

	Culmulative installed capacity (MW) by end of 2000	Installed capacity (MW) in 2000	Forecast 2001–2005					Installed capacity 2001–2005	Culmulative installed capacity (MW) by end of 2005
	2000	2000	2001	2002	2003	2004	2005	Sum	Accumulated
Total America	2847	180	1440	950	1200	1100	1200	5890	8737
Total Europe	13,630	3893	4335	5135	5710	6000	7050	28,230	41,860
Total Asia	1728	330	360	530	680	830	1080	3480	5208
Total other continents and areas	244	93	120	270	425	550	800	2165	2409
Total MW new capacity every year		4495	6255	6885	8015	8480	10,130	39,765	58,214
Accumulated capacity (MW)	18,449	—	24,704	31,589	39,604	48,084	58,214		

10.4. Use the characteristics of Fig. 10.11 to estimate the necessary diameter of a large wind turbine to generate 10 MW of power in a 25 mph wind.

10.5. Explain, using a diagram, the term "tip-speed ratio (TSR)". If the optimum TSR = 6.0 for a two-blade propeller of diameter 180 ft, what speed of rotation in rpm must be used in a 20 mph wind?

10.6. A large propeller-type wind turbine has a diameter of 200 ft. If the speed of rotation at full load is regulated to 32 rpm when the wind speed is 30 mph, what is the value of the tip-speed ratio?

10.7. What are the extreme limits of overall efficiencies for (a) large wind turbine systems, and (b) small wind turbine systems, indicated by the stage efficiency values of Sec. 10.6?

10.8. It is required to generate 1200 watts of electrical power at the terminals of a generator driven through a gearbox by a wind machine. The location is such that the wind supply is of smooth laminar flow with an average speed of 17.5 mph. Assign typical efficiency values to the components of the system and calculate the blade diameter required for a good quality, two-blade propeller type of wind machine. (Air density = 1.29 kg/m^3.)

10.9. A two-blade propeller wind turbine is coupled to a 10 kW electric generator. It is desired to generate 10 kW at the load terminals. The average wind speed is 8 m/s and can be considered as ideally smooth. Assign typical values of efficiency to the turbine and the generator and calculate the necessary diameter of the area swept out by the rotating blades. (Air density = 1.29 kg/m^3.)

10.10. A two-blade propeller is used as a wind turbine directly on the shaft of a small electric generator. Assign typical efficiencies to the wind turbine and the generator and calculate the blade diameter required to generate 500 watts at the load terminals in a wind of average speed 15 mph. ($\rho =$ 1.29 kg/m^2.)

10.11. A two-blade propeller wind machine has a blade diameter 3.5 m and a power coefficient $C_p = 0.36$. What average wind speed in mph would result in 1 kW of power generation if the generator has 70% efficiency?

10.12 (a) A two-blade propeller wind turbine has a blade diameter of 4 m. What average wind speed would result in a power output of 500 W at the generator terminals, assuming typical efficiencies for the generator, the gearbox and the turbine?

(b) At your calculated wind speed, what is the tip-speed ratio if the turbine shaft speed is 40 rpm?

(c) Calculate the diameter of the turbine shaft if the maximum permitted shear stress is 55×10^6 N/m^2.

10.13. A wind-turbine system consists of a two-blade propeller, rotating about a horizontal axis, driving an electrical generator via a gearbox. The generator is required to deliver its rated capacity of 2 MW with the wind turbine rotating at 18 rpm. The maximum permitted shear stress of the solid steel turbine shaft is 55×10^6 N/m^2. The design estimate for the overall efficiency is 30%.

(a) Calculate the torque on the turbine shaft at rated load and the necessary shaft diameter.
(b) Define the term "tip-speed ratio" (TSR), and explain its use in wind energy calculations.
(c) Calculate values for the tip-speed ratio and the required diameter of the propeller if the rated turbine power is developed in an average wind speed of 27.5 mph. (Air density = 1.29 kg/m^3.)
(d) Estimate realistic and consistent figures for the turbine power coefficient, the gearbox efficiency and the generator efficiency.

10.14. A solid-steel cylindrical turbine shaft has a diameter of 12 inches. If the shear stress coefficient $f_s = 55 \times 10^6$ N/m^2, what is the maximum permitted shaft torque?

10.15. The maximum safe rotational speed for a certain wind turbine is 35 rpm. How is this maximum speed retained in high winds? What problems would arise if the speed of rotation became excessive?

10.16. What mechanism is used on the cupola of a Dutch-type windmill to keep the rotating blades facing upstream?

10.17. A Darrieus type of vertical-axis wind generator has no starting torque. How is it usually started up from rest?

10.18. List and briefly discuss the factors that you would take into consideration in selecting a site for a land-based wind machine.

10.19. What order of average wind speed would you expect to find in a "Windy" location within the UK? Sketch the form of the annual variation (January to December) of the effective wind energy flux density in the UK and comment on this.

10.20. What regions of the USA appear to be the most promising for the further development of wind power generation?

10.21. The US city of Chicago, at the southern end of Lake Michigan, has an average wind speed of 10.4 mph and is known as the "windy city". Use figures from the US Meteorological Office to compare the Chicago data with corresponding figures for Cleveland, Ohio, which is on the southern shore of Lake Erie.

10.22. A typical shaft speed for a 10 kW wind machine is 100 rpm. What difficulties does this create with regard to the conversion of the wind energy into electrical energy?

10.23. State the advantages and disadvantages of the possible use of small wind turbines for electricity power generation. For a small two-blade propeller type of machine what is a typical ratio of the output shaft power to the total power available in the wind? If the wind turbine shaft speed is about 50 rpm, what design considerations arise in the choice of a suitable generator?

10.24. Tabulate and discuss the arguments used in favour of and in opposition to large-scale land-based wind turbines.

10.25. Why are the economic prospects of wind-generated electricity in the UK dependent on the retail price of gasoline (petrol) in the USA?

10.26. The jet stream over the North Atlantic ocean travels from west to east at 100 mph. How does this affect (i) the air speed, (ii) the ground speed of 500 mph high-flying jetliners crossing the ocean between Europe and the USA?

10.27. On a certain day the North Atlantic jet stream travels from west to east at 95 mph. If the average air speed of a jetliner is 445 mph, how long is the flight from Manchester, UK to Atlanta, a distance of 3400 miles?

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CHAPTER 11

SOLAR HEATING OF WATER OR AIR

11.1. Radiation from the Sun

Our sun is a fairy typical star that astronomers call a G-type “main sequence star”. It exists in what we believe to be an average galaxy called the Milky Way that is rich in gas and stellar dust and has a diameter of about 100,000 light years.

The sun is a large mass of burning gases, mainly hydrogen and helium, with a diameter of about 1.4 million km (860,000 miles). At its interior core, occupying about a quarter of the cross-section diameter, the intense heat is estimated to be at a temperature of 20 million kelvins (2×10^7 K). In this so-called plasma region, atomic hydrogen fuses to form stable helium, with the generation of high frequency gamma radiation and the release of large amounts of energy which fuel the ongoing chemical reaction.

Energy generated within the solar core is radiated and convected to the solar surface, which, in the present context, may be regarded as a uniform spherical black-body radiator at a temperature of about 5800 K.

Solar radiation spans a large portion of the whole electromagnetic spectrum. For example, the sun is a very strong radio source. However, radio waves have negligible energy. The vast majority of the sun’s radiated energy is concentrated between wavelengths 300 nm (0.3 μm) and 3000 nm (3 μm), with the spectral distribution shown in Fig. 11.1. This range of wavelengths extends both into the near ultraviolet and into the near infrared regions. Interestingly, integration between the limits of optically visible light (400–750 nm) reveals that it contributes about 45% of the total solar radiated energy per unit area at the earth’s mean distance of 150 million km (93 million miles) from the sun.

All of the radiation travels at the velocity of electromagnetic wave propagation c to satisfy the relationship

$$c = \lambda f \tag{11.1}$$

where f is the frequency in hertz and λ is the wavelength in metres. Velocity c has the value 2.998×10^8 m/s. The region of visible light lies in the frequency range 4.0–7.5×10^{14} Hz.

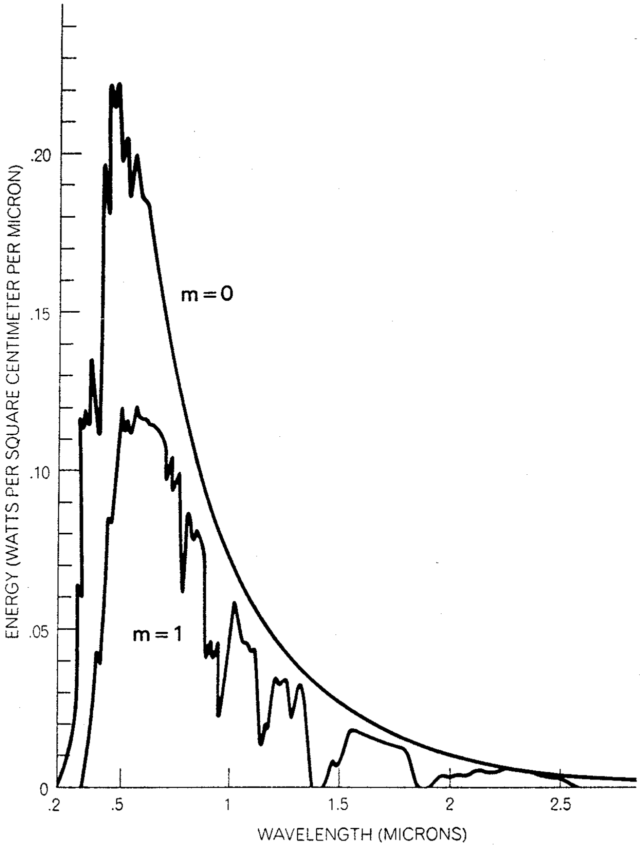


Fig. 11.1. Solar spectral irradiance (courtesy of *Scientific American*, USA).

The larger spectral contour of Fig. 11.1 represents the radiated solar energy falling normally (i.e. perpendicularly) onto a receiver just outside the earth's atmosphere. It is sometimes called the $m = 0$ characteristic because, in that location, there is zero mass of air between the transmitter (the sun) and the spectral receiver (the earth). Outside the earth's atmosphere the sun power or solar insolation flux has a value of 1.36 kW/m^2 or 0.136 W/cm^2, which is referred to as the *solar constant*. At sea level with zero zenith angle, the column of air through which the radiation passes reduces the average received power to about 1 kW/m^2. This is shown as the $m = 1$ characteristic in Fig. 11.1 and Fig. 11.2. At various different wavelengths, the received ground level radiation has been differently inhibited due to absorption by water vapour or atmospheric gases such as oxygen (O_2) or carbon dioxide (CO_2).

The intensity of the radiation or solar insolation on a surface depends on:

(i) obliquity — the angle between the surface and the beam of radiation
(ii) the length of air mass through which the radiation has to pass.

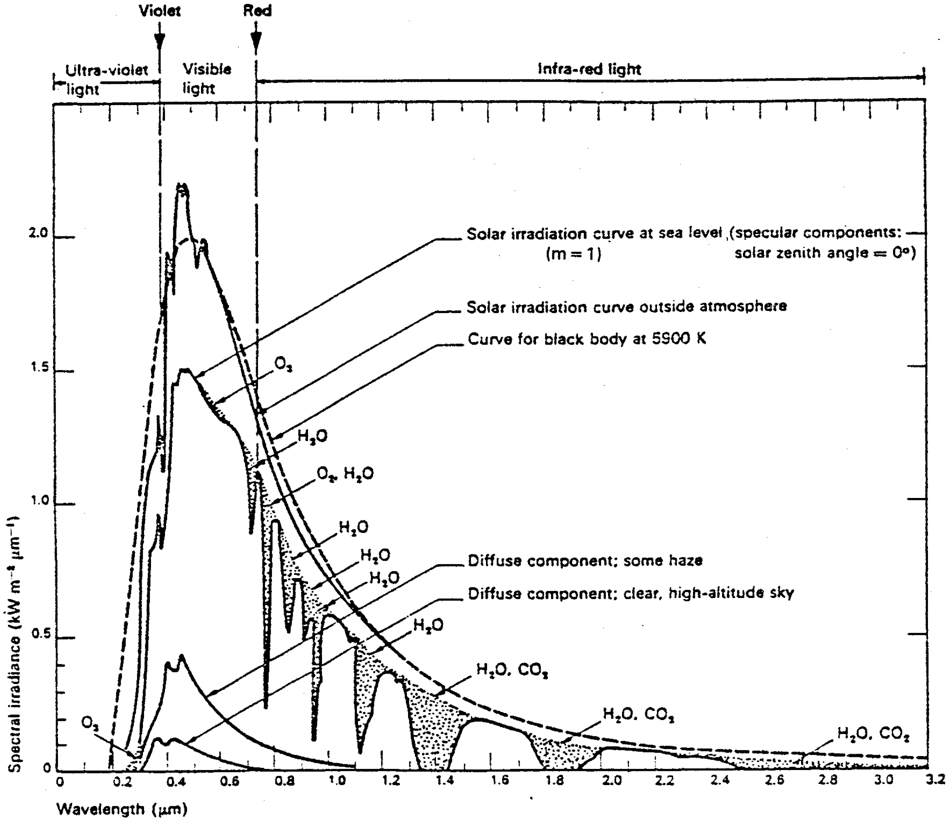


Fig. 11.2. The solar spectrum outside the atmosphere and at ground level [4].

Both of the factors (i) and (ii) depend on the altitude of the sun above the ground. In Northern Europe the maximum solar altitude is 15° in midwinter, which corresponds to an air mass $m = 4$.

In the UK the average annual solar insolation at ground level is about 100 W/m^2. In the summer months the peak insolation rises to about 1 kW/m^2 but this exists only for about an hour at midday.

The passage of the solar radiation through the earth's atmosphere is illustrated in Fig. 11.3. Some radiation is received at ground level by direct and uninterrupted transmission and this is referred to as the *direct component* of radiation. Some component of the radiation is reflected off the clouds and back into space, while another component is absorbed by atmospheric dust or gas clouds. The presence of gas molecules or dust particles in the atmosphere cause some rays of sunlight to be deflected by scattering. Each collision causes the incoming radiation to lose some of its energy, which has the consequent effect of increasing the wavelength. The sum of the various effects of reflection, scattering and absorption is known as the *diffuse component* of radiation. The relative amounts of direct and diffuse radiation vary

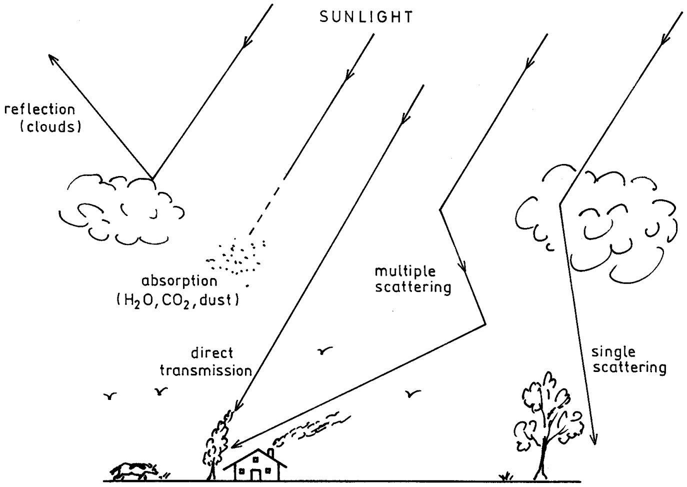

SUNLIGHT
reflection (clouds)
absorption (H_2O, CO_2, dust)
multiple scattering
direct transmission
single scattering

Fig. 11.3. Interaction of sunlight with atmosphere (courtesy of Dr M. Munroe).

Table 11.1. Solar intensity values (on horizontal surface) [2].

		kWh/m^2					
		Max. bright day		Min. dull day		Yearly total	
Location	Latitude	(1)	(2)	(1)	(2)	(1)	(2)
Equator	0°	6.5	7.5	5.8	6.8	2200	2300
Tropics	23.5°	7.1	8.3	3.4	4.2	1900	2300
Mid-earth	45°	7.2	8.5	1.2	1.7	1500	1900
Central UK	52°	7.0	8.4	0.5	0.8	1400 (900 due to atmospheric conditions)	1700
Polar circle	66.5°	6.5	7.9	0	0	1200	1400

(1) Direct sunlight
(2) Direct + diffuse sunlight

greatly in different parts of the world and for different times of the year. In the UK the direct and diffuse components of energy are roughly equal in magnitude, as illustrated by the month-by-month data of Fig. 11.4 [1].

Additional information about the extent of solar energy falling onto a horizontal surface, at ground level, is given in Table 11.1 [2].

The diffuse radiation is assumed to be uniform in all directions and is defined as D. If the direct-incident radiation is I, then the total global radiation on a surface

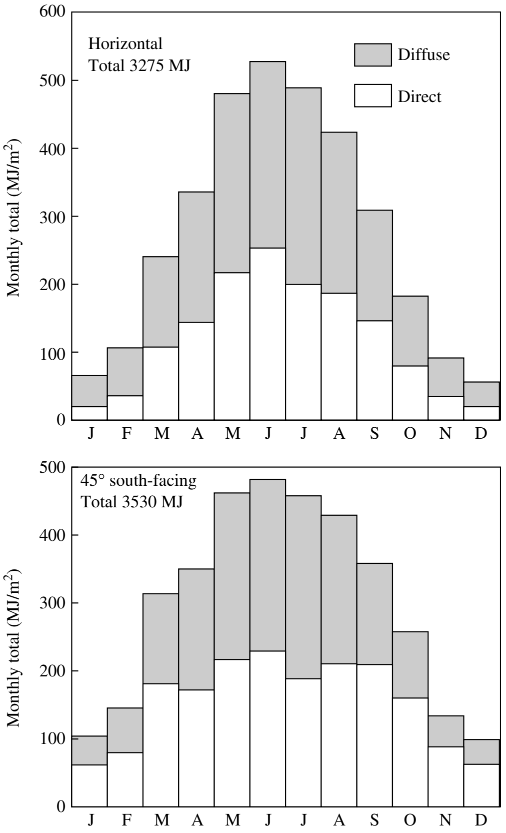


Fig. 11.4. Solar radiation data for London, England [1].

G is [3]

$$G = D + I \sin \gamma \tag{11.2}$$

where γ is the angle of the solar altitude above the horizon.

The unit of energy in Table 11.1 is the kilowatt hour (kWh), which is the energy unit used in the domestic electricity meters. In electrical energy measurements the kilowatt hour is often called a *unit* of electricity. By contrast the energy unit in Fig. 11.4 is the megajoule (MJ). It is seen from the Table of Conversion Factors, Table 1.5 of Chapter 1, that 1 kWh = 3.6 MJ. Table 11.1 shows that in many parts of the northern hemisphere the solar energy total in a year at ground level is about 900 kWh/m^2 [2, 3]. This is a tremendous amount of energy, with enormous potential.

The total amount of solar energy falling on the earth, as discussed in Sec. 2.1.1 of Chapter 2, is staggeringly large — more than enough for present human needs and amply sufficient to meet any anticipated future demand. For the USA or any of the European countries the average annual solar insolation is several hundred times the total energy needs. But serious difficulties exist with regard to efficient and economic energy extraction, conversion and storage which inhibit the attractiveness of solar energy. The main problems are the low intensity of the radiation at ground level and its intermittent nature. Nonetheless, the sun is a source of free, non-polluting and infinitely renewable energy.

11.2. Seasonal Variation of Solar Radiation

As the earth circuits the sun every 365 1/4 days, it makes one complete rotation every day about its axis. The axis of rotation is tilted at 23.44° from the normal to the ecliptic plane, Fig. 11.5 [4]. This is why the latitude lines marking the Tropic of Cancer and the Tropic of Capricorn are each displaced by 23.44° from the earth's equator. The solar radiation strikes the equatorial regions of the earth much more squarely (i.e. it has a low zenith angle) than it does the polar regions. For this reason the solar flux at ground level is roughly dependent on latitude. In Fig. 11.6

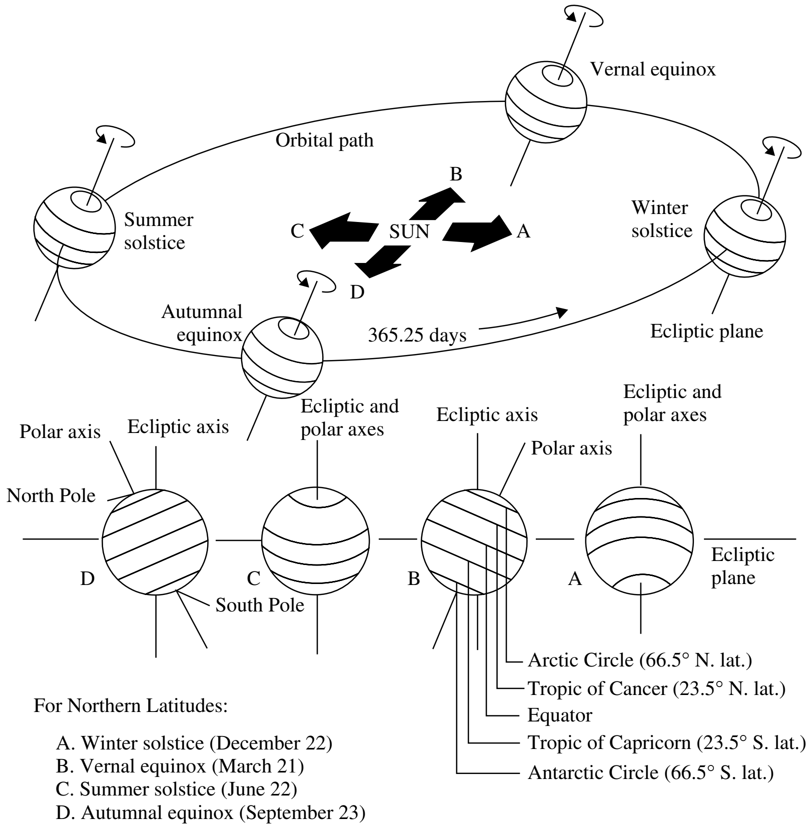

Vernal equinox
Orbital path
B
Summer solstice
C
SUN
A
Winter solstice
D
Autumnal equinox
365.25 days
Ecliptic plane
Ecliptic and polar axes
Ecliptic axis
Ecliptic and polar axes
Polar axis
Ecliptic axis
Polar axis
North Pole
D
C
B
A
Ecliptic plane
South Pole
Arctic Circle (66.5° N. lat.)
Tropic of Cancer (23.5° N. lat.)
Equator
Tropic of Capricorn (23.5° S. lat.)
Antarctic Circle (66.5° S. lat.)
For Northern Latitudes:
A. Winter solstice (December 22)
B. Vernal equinox (March 21)
C. Summer solstice (June 22)
D. Autumnal equinox (September 23)

Fig. 11.5. Orientation of the earth with respect to solar radiation [4].

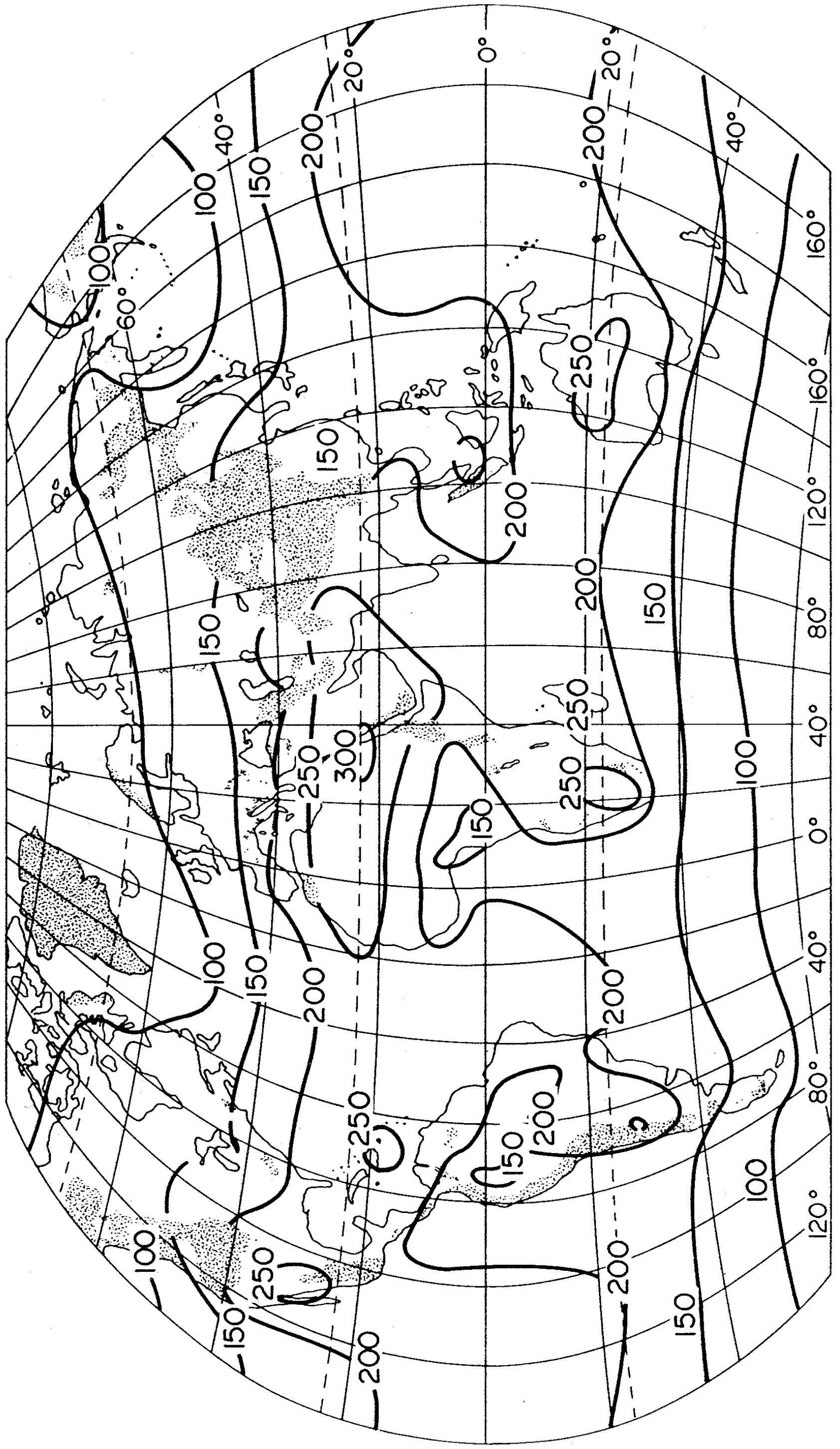

0°
20°
20°
40°
40°
60°
160°
160°
120°
80°
40°
0°
40°
80°
120°
100
150
200
250
300

Fig. 11.6. Annual mean global solar radiation on a horizontal plane at the earth's surface, W/m^2 [5].

the mean annual radiation is divided into zones of ground level intensity [3, 5]. It can be seen that the regions of greatest mean annual solar intensity coincide largely with desert regions, where the radiation falls on land masses.

The range 100 W/m^2 in the projection of Fig. 11.6 includes Northern Europe and the British Isles. But it also includes the permafrost regions of the Northern Territories of Canada and the Siberian Territories of Russia. The winter air temperatures in Great Britain, for example, are very much milder than Northern Canada and Russia because of the moderating effects of ocean currents, notably the Gulf Stream. For Great Britain the mean annual solar power received is about 100 W/m^2 on average, with a monthly distribution that peaks in June. By comparison, Egypt and Sudan (for example), in northern Africa, receive about 300 W/m^2 and the month-by-month distribution is much flatter.

Contours of total solar radiation for the British Isles are given in Fig. 11.7 for astronomical high summer (the summer solstice is June 22) and astronomical midwinter (the winter solstice is December 22) [1]. The ground-level solar radiation is higher in the west than the east in England and Wales because of cloud cover and the prevailing westerly winds. The most striking feature of the data of Fig. 11.7 is that there is a magnitude factor of 10 to 1 between the radiation figures for midsummer and midwinter. In Britain the solar radiation is strongest in the summer

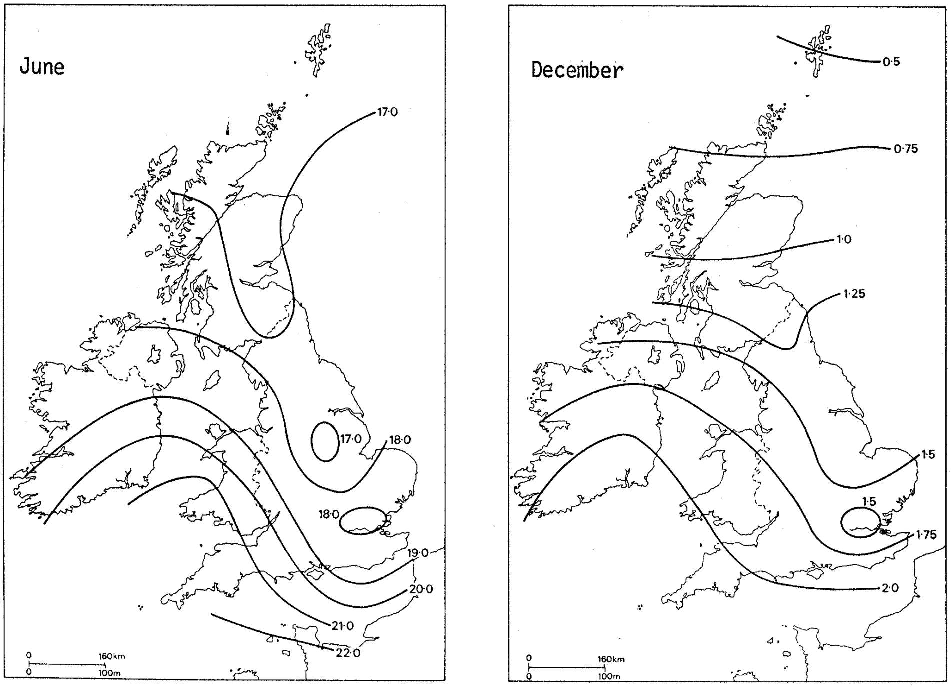


Fig. 11.7. Average daily solar radiation in the UK, MJ/m^2 [1].

at the time of the year when the energy demand is least, in both the domestic and industrial sectors. One might describe the situation by saying that, in Britain, the incoming solar radiation is in time anti-phase with the demand for electricity (shown in Fig. 3.8 of Chapter 3). It should be noted that there are other countries where the levels of incoming solar radiation match the energy demand. In the southern areas of the USA, for example, the demand for electricity is much greater in the summer than in the winter because of the widespread use of air-conditioning (cooling) and refrigeration equipment.

In the plot of solar power input versus time, the area under the curve has the dimension of power times time, which is energy. The striking contrast of the energy content of the incoming UK solar radiation between summer and winter is illustrated by the relative areas under the two curves of Fig. 11.8.

A feature of the British climate is the large variations of solar radiation that exist from day to day. Figure 11.9 shows actual recordings of the solar input at a particular location in Northern England from sunrise to sunset. The frequent dips in the traces [Fig. 11.9(b)] are due to cloud motion across the sky. The energy input on a horizontal surface, obtained by calculating the areas under the curves of

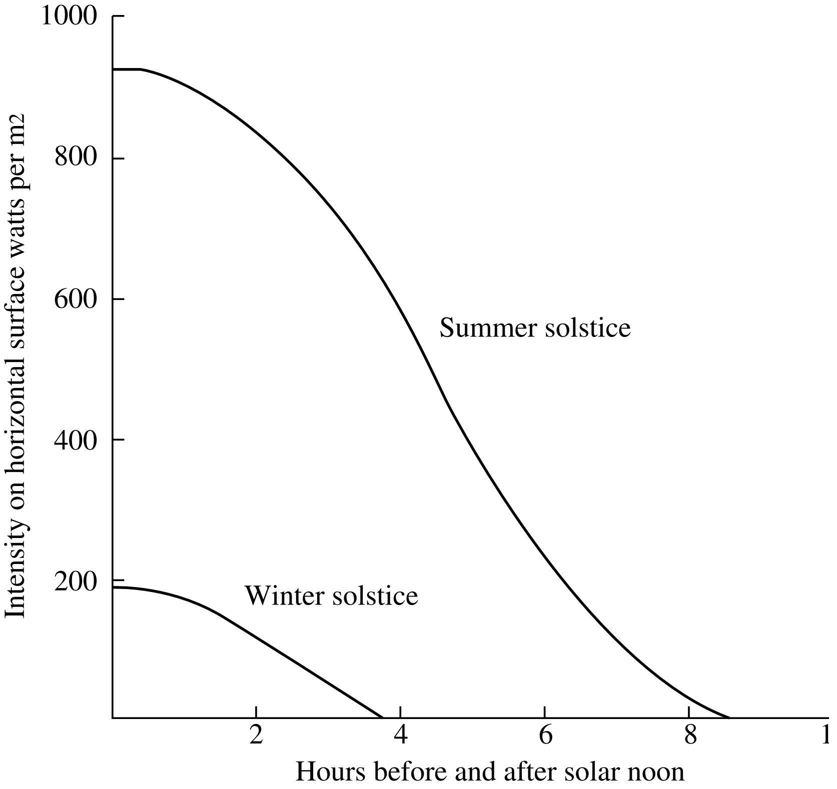
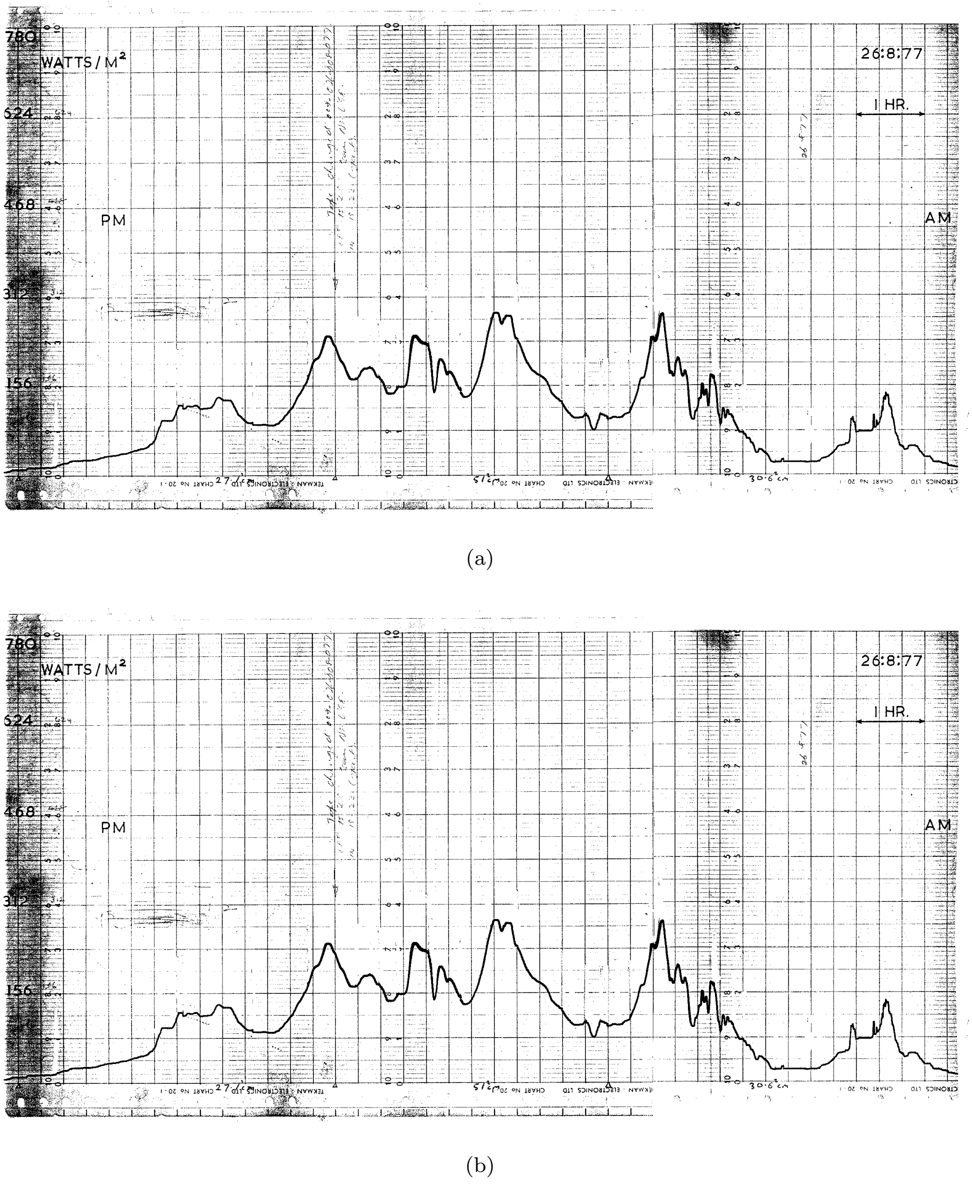


Fig. 11.8. Solar power density (W/m^2) versus time for the UK.



(a)

(b)

Fig. 11.9. Solar radiation recordings in Central England, W/m^2.
(a) Overcast, (b) bright and sunny.
(Ref: M. Munroe, PhD thesis, Bradford, UK, 1977.)

Table 11.2. Measured solar data at the University of Bradford, England, 1977.

Date	Climate condition	Hours of daylight	Peak insolation W/m^2	Energy content kWh/m^2
26/8/77	overcast and rain	15	202	1.3
7/9/77	intermittent sunshine	14	450	2.6
15/9/77	bright and sunny	13	780	4.5

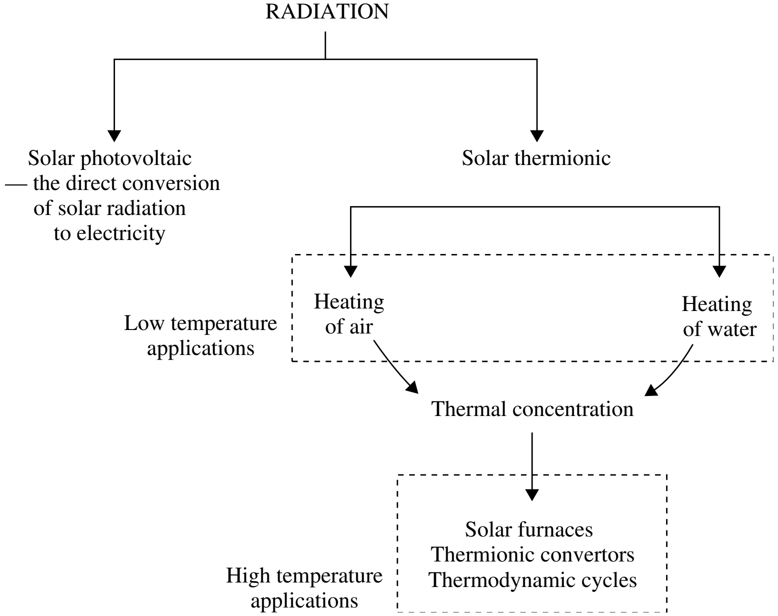

RADIATION
Solar photovoltaic — the direct conversion of solar radiation to electricity
Solar thermionic
Heating of air
Heating of water
Low temperature applications
Thermal concentration
Solar furnaces
Thermionic convertors
Thermodynamic cycles
High temperature applications

Fig. 11.10. Categories of solar energy collection.

Fig. 11.9, demonstrates typical climatic behaviour. This is given in Table 11.2. At the same period of the year there can be a 3:1 difference in the solar energy input, dependent on local weather conditions.

11.3. Classification of the Collection of Solar Energy

Solar energy collection systems fall into three broad categories, as illustrated in Fig. 11.10. These categories are:

(i) The direct conversion of sunlight into electricity by the use of photovoltaic cell;

(ii) The direct heating of air or water to give a thermal output below 150°C. This area of thermionic technology is oriented towards domestic applications in the heating of buildings and/or hot water supply;

(iii) Thermionic concentrator systems for producing high temperature (i.e. above 150°C) heat energy for, for example, thermodynamic (i.e. heat–mechanical work) systems.

Various applications of solar thermionic systems are discussed in Secs. 2.4 and 2.5 of Chapter 2. Photovoltaic conversion is discussed in Chapter 12.

11.4. Solar Water Heating (Domestic)

There are many Roman remains in various parts of Europe and the Mediterranean countries, some now 2000 years old, that demonstrate that the Romans used solar water heating. Open water channels feeding the bath houses were lined with grooved black slate to increase the heat absorption.

About a quarter of all the energy consumed in the USA and European Community countries at present is used for low-grade heating or cooling purposes. Much of this is used to heat the air in buildings — usually called space heating — or to heat water for domestic purposes. The most common form of domestic solar water heater employs the "greenhouse" effect, described below.

11.4.1. *The "greenhouse" effect*

Glass has a high coefficient of transmittance for radiation within the spectral range $0.3 \leq \lambda \leq 3$ microns (μm). Within this waveband about 90% of the incident radiation is transmitted, although the transmittance is not equal at all wavelengths. For radiation of wavelength $\lambda > 3$ μm the transmittance falls below 25% and in the region $4 \leq \lambda \leq 15$ μm the transmittance is virtually zero, Fig. 11.11. In other words, the transmittance properties of glass are such that glass is a low-pass filter in terms of radiation wavelength. The pass band of the radiation transmission includes the range of human visibility and much of the useful infrared range.

Much of the incident radiation in the infrared region, with $\lambda > 4$ μm, is reflected back from the greenhouse surface [Fig. 11.12], but gives up some of its energy to the glass.

When solar radiation passes through the glass, collisions between some photons of the electromagnetic radiation and some molecules of the glass causes a certain amount of the incident energy to be dissipated in heating the glass. The loss of energy suffered by the incoming radiation is accompanied by an increase in wavelength. After the increased wavelength radiation enters the greenhouse enclosure [Fig. 11.12], some of it undergoes reflections or refractions. Each of these changes of direction is accompanied by a proportion of energy loss and wavelength increase. The net effect is that the increased wavelength prevents much of the internal radiation from being re-transmitted outwards. It undergoes multiple reflections, scattering and absorption until its incident energy is all dissipated. The overall effect

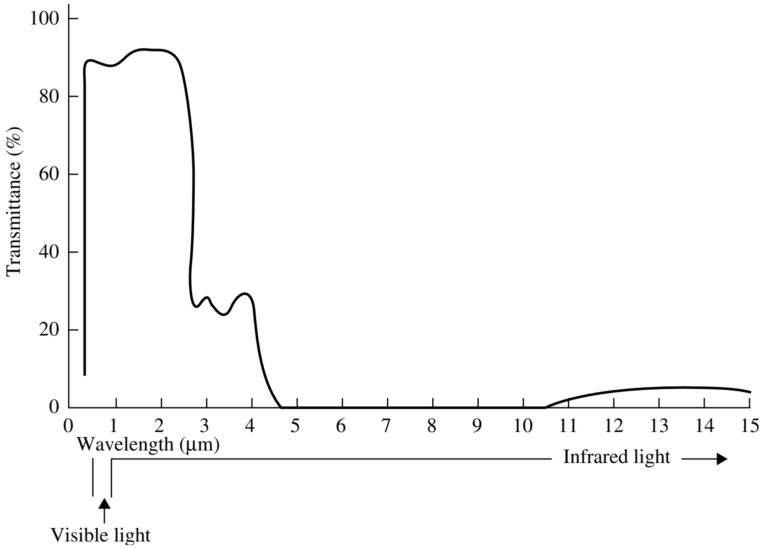


Fig. 11.11. Transmittance of window glass as a function of wavelength [4].

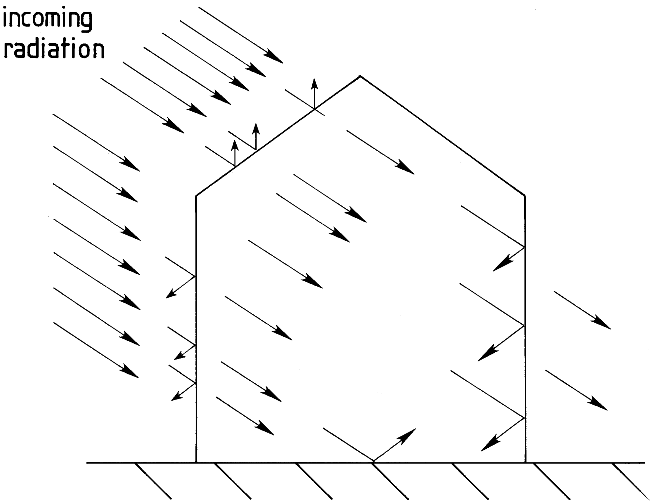


Fig. 11.12. Radiation pattern illustrating the greenhouse effect.

is a temperature rise until the incoming energy balances the heat losses due to conduction, convection and re-radiation. At night, when the incoming radiation ceases, a lot of the greenhouse heat energy is lost by re-radiation outwards and the temperature falls.

In Great Britain one of the common hobbies is gardening. The ground temperature and air temperature during the winter can sometimes fall below the freezing point of water (0°C or 32°F). When this happens many forms of plants would suffer severe damage, due to ice and snow or simply due to freezing cold air. Experienced gardeners know which plants to leave outdoors over the winter period and which must be taken indoors.

Many gardeners use a glass-enclosed shed, called a "greenhouse" because the contents are the green foliage of living and growing plants. Some greenhouse structures are built as conservatories and share a common wall with the main house, in the style of Fig. 11.27. Other greenhouses are small glass enclosures that are physically independent of other buildings. It is an interesting experience to walk into a UK greenhouse in midwinter when the outside temperature is below the freezing point. Even without any form of local heating the air temperature inside the greenhouse remains well above freezing, due to solar radiation, and is perceptibly warmer than outside. In the summertime greenhouses experience a large solar gain of energy so that they must be shaded and ventilated if excessive temperatures are to be avoided.

11.4.2. *Solar flat-plate collectors*

Most domestic solar water heater collectors in the UK are referred to as flat-plate collectors. The term "flat-plate collector" is rather misleading and is used to define a wide variety of collectors having different geometries (some of them being far from flat), different heater fluids and different methods of heat transfer.

A typical collector panel is illustrated in Fig. 11.13. The collector is a metal plate that is ribbed or corrugated so that a fluid (usually water) passes through it or over it. A common form of structure is similar to that of a central heating radiator in a pumped water system. The surface of the solar collector is exposed to the incoming radiation and is coated black for maximum radiation absorption. Usually the collector is contained within some enclosure that has a glass or transparent plastic cover, to retain its collected heat. As described in the previous section, the greenhouse effect can cause high temperatures to exist within the collector enclosure. Heat is transferred from the metal of the collector to an outside energy reservoir by pumping water through the collector. Even so, on a warm summer day a collector becomes much too hot to be touched by hand. Collectors are often roof-mounted and inclined at the latitude angle to be perpendicular to the incident radiation.

In flat-plate collectors the incoming radiation is not concentrated optically as in the higher temperature collector systems described in Sec. 11.5 below. The collector area is equal to the absorbed area because both functions are incorporated into the same collector device (i.e. the flat plate). Using the terminology of Sec. 11.5, one could say that a flat-plate collector has a concentration ratio of unity.

About one half of the incident energy falling onto the collector is subsequently re-emitted. The absorbance (or absorptance) of solar energy causes the blackened

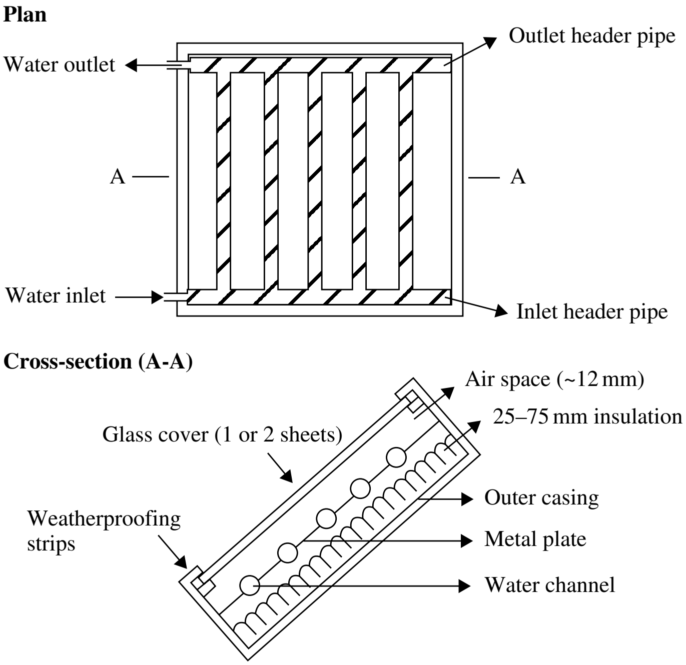

Plan
Water outlet
Outlet header pipe
A
A
Water inlet
Inlet header pipe
Cross-section (A-A)
Air space (~12 mm)
25–75 mm insulation
Glass cover (1 or 2 sheets)
Outer casing
Metal plate
Water channel
Weatherproofing strips

Fig. 11.13. Structure of flat-plate solar collector.

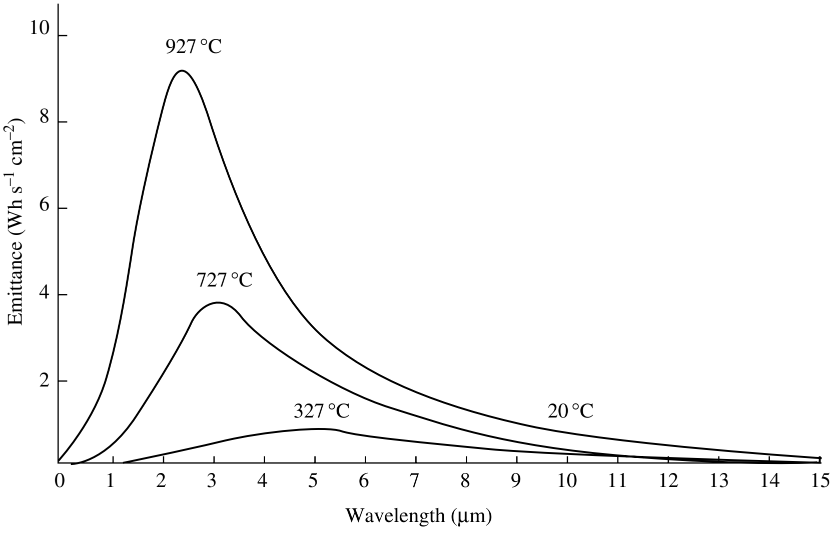


Fig. 11.14. Emittance of a black body versus wavelength [4].

collector temperature to rise and its re-emitted radiation then has a slightly shorter wavelength. It is found that some of the energy re-radiated from the black collector has wavelengths in the range $4 \leq \lambda \leq 15$ μm and cannot exit through the glass cover of the container. Part of this entrapped radiation is reflected from the glass cover sheet back onto the collector plate.

The radiation emittance property of an ideal black body radiation varies with the frequency (or wavelength) of the radiation and also depends on the black body temperature. For example, the radiation surface of the sun behaves like a black body with a temperature of 5800 K and its emittance versus wavelength characteristic is given in Fig. 11.2. Similarly, emittance characteristics for several other temperatures are given in Fig. 11.14 [4]. The feature whereby the emittance can be related to the temperature of the black radiating body is a useful measure of the effectiveness of a solar collector.

Selective coatings are available for the solar collector, to increase its absorbance and reduce its re-emittance. Even without a glass cover the deposition of thin films of a metal such as beryllium can greatly improve the collector performance. The use of the cover, however, contributes to the vital greenhouse effect and gives thermal insulation against loss of the heat to the ambient air by conduction and convection.

Table 11.3. Solar absorptance (α) infrared emittance (ϵ_{IR}) for various selective coatings.

Material	Solar absorptance (α)	IR emittance (ϵ_{IR})	Performance factor α/ϵ
Copper oxide on copper	0.90	0.12	7.5
Black nickel on copper	0.90	0.08 (573 K)	11
Black chrome on copper	0.95	0.12	7.92
Silicon on silver	0.76	0.06 (773 K)	12
Nonmetallic black surfaces: asphalt slate, carbon	0.92	0.94	0.98
Flat black paint	0.97	0.86	1.13
3M Velvet black paint	0.98	0.90	1.09
Grey paint	0.75	0.95	0.79
Red brick	0.55	0.92	0.6
Concrete	0.60	0.88	0.68
Galvanised steel	0.65	0.13	5
Aluminium foil	0.15	0.05	3
ZrNy on Ag	0.85	0.03 (600 K)	24

Ref.: Table 11.3 is slightly modified from an original given in:
Engineers' Guide to Solar Energy
Y. Howeel, J. A. Bereny
Solar Energy Information Services
PO Box 204, San Mateo, CA 94401, USA, 1979

A listing of some relative selective industrial coatings is given in Table 11.3, in which the solar emittance is also defined in terms of black body temperature. The aim is to achieve maximum absorbance α and minimum re-emittance ϵ so that the ratio α/ϵ is a maximum.

Selective coatings are also available in the form of paints. These tend to be very expensive compared with standard decorating paints. The authors have found that for domestic use and for student projects any standard form of matt black paint gives good results and represents good value for money.

The efficiencies of solar water collectors with different enclosure coverings are shown in Fig. 11.5, in which the independent (x-axis) variable is the difference $(T_c - T_a)$ between the collector fluid temperature T_c and the ambient air temperature T_a divided by the incident radiation in W/m^2 [3]. The glazing should possess the properties of resistance to ultraviolet ray deterioration, good thermal stability, durability in harsh weather and mechanical strength and rigidity, combined with low cost.

When only a small temperature rise is required, as in swimming pool heating, high efficiency can be obtained by using solar water collector panels that are completely unglazed. In the UK this form of swimming pool heating is widely used during the summer months. In the USA the largest end use for solar collectors shipped during 1999 (95% of total shipments) was for heating swimming pools [6].

In domestic hot water systems the maximum required working temperature is usually not more than 60°C. Temperature rises of 20–40°C may be desired. For such applications the solar collector enclosure should be thermally insulated and some

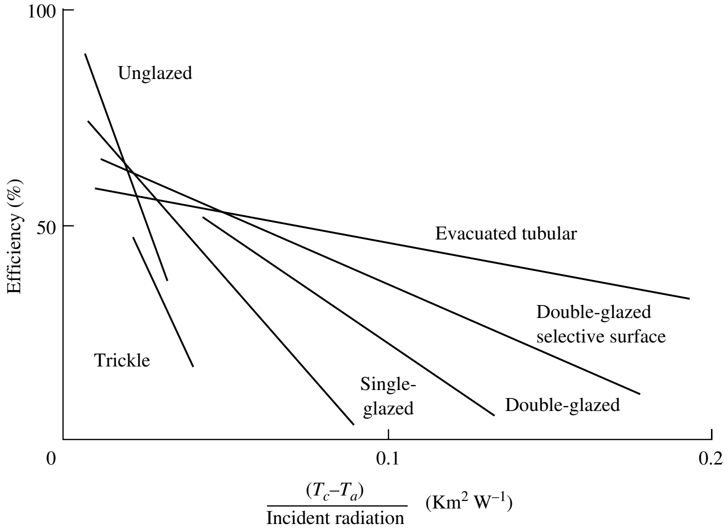


Fig. 11.15. Efficiency of solar water collectors [3].

form of glazed cover is required. Such collectors usually operate with an efficiency of the order 40–50%.

Under steady-state conditions the heat energy delivered by a flat-plate solar collector is the heat energy absorbed by the plate minus the heat losses from the plate to the surroundings. This can be expressed in mathematical form by the empirical equation following [3],

$$Q = F[G\tau\alpha - U(T_c - T_a)] \tag{11.3}$$

where

F = design factor of the collector construction (collector heat removal efficiency factor)
G = total normal incident radiation, W/m^2
Q = quantity of heat collected per unit area of collector
T_a = ambient temperature outside the collector enclosure, K
T_c = collector fluid temperature, K
U = heat loss coefficient per degree of temperature difference $T_c - T_a$
α = absorbance of collector plate (the fraction of radiation reaching the absorber plate that is actually absorbed). Absorbance properties of various materials are listed in Table 11.3.
τ = transmittance of enclosure cover (fraction of G transmitted through the cover plates). Transmittance properties of various materials are listed in Table 11.4.
$\tau\alpha$ = design factor which takes into account multiple reflections and absorption in the cover glazing.

The thermal performance is defined by the three design factors F, $\tau\alpha$ and U. Values of these are given in Table 11.5, for a range of commercial flat-plate collector systems.

The thermal efficiency of the collector is the proportion of the total incident power G that is converted into usable heat. If the collector thermal efficiency is denoted by η_c, then

$$\eta_c = \frac{Q}{G} = F\left[\tau\alpha - \frac{U}{G}(T_c - T_a)\right] \tag{11.4}$$

Equations (11.3) and (11.4) are valid for any self-consistent set of units. It is seen from (11.4) that the efficiency varies inversely with the temperature difference $T_c - T_a$, as indicated by the characteristics of Fig. 11.15.

Another empirical form for the efficiency relationship of a glazed collector when only the input radiation and temperature values are known is

$$\eta_c = 0.78 - \frac{7.7(T_c - T_a)}{G} \tag{11.5}$$

where T_c, T_a are in degrees centigrade or Kelvin and G is in W/m^2 [3]. Note that (11.5) cannot be made the subject of detailed conceptual analysis. For example, a direct examination of (11.5) suggests that the maximum collector efficiency is 78%. This would be true mathematically if $T_c = T_a$. But if $T_c = T_a$ there is no thermal gain and the collector is not giving any output, so the system efficiency is zero. The use of (11.5) is restricted to practical situations and practical ranges of collector operation.

If $G\tau\alpha \leq U(T_c - T_a)$ in (11.4) the efficiency is mathematically negative. This means that the collector losses are greater than the incoming solar energy. The

Table 11.4. Solar transmittance (τ) for various cover-plate materials; the exact value depends on the cover thickness and the direction of the solar beam. (Various sources.)

Material	Transmittance (τ)
Crystal glass	0.91
Window glass	0.85
Polymethyl methacrylate (acrylic) Acrylite Lucite Plexiglass	0.89
Polycarbonate Lexan Merlon	0.84
Polyethylene terephthalate (polyester) Mylar	0.84
Polyvinyl flouride Tedlar	0.93
Polymide Kapton	0.80
Polyethylene	0.86
Fluorinated ethylene propylene (fluorocarbon) FEP Teflon	0.96
Fibreglass-reinforced polyester Kalwall	0.87
Fibreglass-reinforced, acrylic-fortified polyester with polyvinyl fluoride weather surface Tedlar-clad Filon	0.86

Ref.: *Engineers' Guide to Solar Energy*
Y. Howell, J. A. Bereny
Solar Energy Information Services
PO Box 204, San Mateo, CA 94401, USA, 1979

Table 11.5. Performance parameters of certain commercial solar flat-plate collectors.

Collector source	Absorber material	Absorber surface coating	Transparent covers	F_R	U_L		τ_α	α	ε	τ
					$\frac{\text{Btu}}{\text{hft}^2\text{F}}$	$\frac{\text{W}}{\text{m}^2\text{C}}$				
NASA/Honeywell	Aluminum	Black nickel	2 Glass	0.94	0.56	3.2	0.74	0.95	0.07	0.78
Marshall Space Flight C.	Aluminum	Black nickel	2 Tedlar	0.95	0.69	3.9	0.56	0.73	0.1	0.77
NASA/Honeywell	Aluminum	Black paint	1 Glass	0.90	1.3	7.4	0.89	0.97	0.97	0.92
NASA/Honeywell (mylar honeycomb)	Aluminum	Black paint	2 Glass	0.96	0.57	3.2	0.77	0.97		0.79
NASA Honeywell	Aluminum	Black paint	2 Glass	0.93	0.80	4.6	0.76	0.97	0.97	0.78
PPG Industries	Aluminum	Black paint	2 Glass	0.85	1.1	6.2	0.73	0.95	0.95	0.77
Owens-Illinois (evacuated tube)	Glass	Selective surface	1 Glass	0.75	0.20	1.1	0.72	0.8	0.07	0.9
Solaron (data furnished by manufacturer). Heat transfer fluid is air.	Steel	Black paint	2 Glass	0.67	0.77	4.4	0.73	—	—	—

Ref.: "Solar Heating and Cooling of Residential Buildings: Design of Systems". Government Printing Office, Washington DC, USA, 1977. (Report on work at Colorado State University.)

physical conditions under which this is likely to occur are when the collector mass is warm from previous operation, the ambient air temperature is low and the incoming radiation falls to a low value.

A detailed design of a solar collector is outside the scope of the present book. Such design is partly empirical and requires knowledge of the scope and range of the design factors U and F, which are usually determined by experience. The various terms of (11.4) do, however, suggest several strategies that might be employed in improving the efficiency of the collector. It is seen that various terms in (11.4) must increase or decrease, as follows, if an increase of η_c is to be realised:

design factor $F, \uparrow$
effective incident radiation $G, \uparrow$
transmittance $\tau, \uparrow$
absorptance (absorbance) $\alpha, \uparrow$
heat loss coefficient $U, \downarrow$
temperature difference $(T_c - T_a), \downarrow$
collector fluid temperature $T_c, \downarrow$

Suggested methods of change and the likely effects on collector performance are summarised in Table 11.6. Any change that will reduce the heat losses due to conduction, convection or re-radiation is likely to increase the collector working efficiency. If any proposed change involves increased expenditure it will be necessary to undertake an economic analysis to assess if such a change represents an overall cost saving. For example, is the increased installation cost justified by reduced running costs? Over what period of time would the investment be recovered?

Table 11.6. Improving the efficiency of flat-plate solar collectors.

Desired parameter change	**Method of change**	**Effect on the collector**
$F \uparrow$	improved geometry of collector	better heat transfer from radiation to collector
$G \uparrow$	concentration of incident radiation — south facing and tracking	higher thermal input
$\tau \uparrow$	selective windows	reduced radiation losses
$\alpha \uparrow$	selective absorber on collector	increased absorbance and reduced emittance
$U \downarrow$	e.g. double glazing, better insulation	reduced conduction and convection losses
$(T_c - T_a) \downarrow$ $T_c \downarrow$	reduced working fluid temp	reduced conduction and radiation losses

11.4.3. *A typical domestic solar water heating system*

The solar radiation in any particular location undergoes daily and seasonal variations. Sometimes the solar input is not adequate for the intended use and a back-up supply of energy is required. On other occasions the solar input energy may exceed the immediate demand and the excess energy must be wasted or put into storage. The successful long-term (i.e. weeks and months) storage of heat energy is a scientific, engineering and economic problem that has not yet been solved. For domestic hot water systems it is usually required that the heat energy be stored for only a few hours.

A typical form of solar-assisted domestic hot water system is shown in Fig. 11.16 [1]. The collector should be mounted facing due south, in the northern hemisphere, and inclined at the latitude angle. For example, central UK is of latitude 54°N so the collector should be inclined at 54° to the horizontal. Where such a precise orientation is not possible it is a reasonable compromise to mount the collector on the sloping roof of a house provided that the roof is, at least, partly south-facing and is not screened by other buildings or trees. The collector fluid is restricted inside a self-contained pipe system and heat is transferred using a copper coil pipe immersed inside a supplementary domestic storage tank. The water, or other fluid, in the solar collector circuit can be circulated using a small electric pump, of the size used in domestic central heating systems (rated at tens of watts). This should be temperature-actuated to switch on when the collector fluid temperature T_c exceeds the supplementary tank temperature T_t. Suitable pumps, with temperature-sensitive controllers, can be purchased commercially.

With the "indirect" solar collector system of Fig. 11.16, the fluid in the solar collector circuit is completely separate from the water of the domestic hot water system. Where a solar collector system is added (retrofitted) to an existing house or other building, then it is good practice to install a supplementary storage tank, as in Fig. 11.16.

In the system of Fig. 11.16 water from the cold water supply is fed into the bottom of supplementary tank A. This water is heated due to heat transfer from the solar heated water in the solar coil. The solar pre-heated water is then piped to the main storage tank B, from which it can be drawn off for domestic use. It is customary in the UK to use an electrical "immersion" heater as a back-up facility. Alternatively, the main storage tank water may be heated via a gas-heated or oil-heated furnace. The pre-heating created by the solar collector system means that less fuel is used in raising the water temperature in the main storage tank.

It is possible to implement systems using only one storage tank. The solar collector circuit and the building heating system both heat the water in the same storage tank, which acts as a heating source for the hot water supply [7].

Some solar collector systems do not use a pump but rely on the natural convection of the heated water to circulate itself. This is sometimes called a thermosyphon effect. In Japan, for example, there are several million small solar water heating

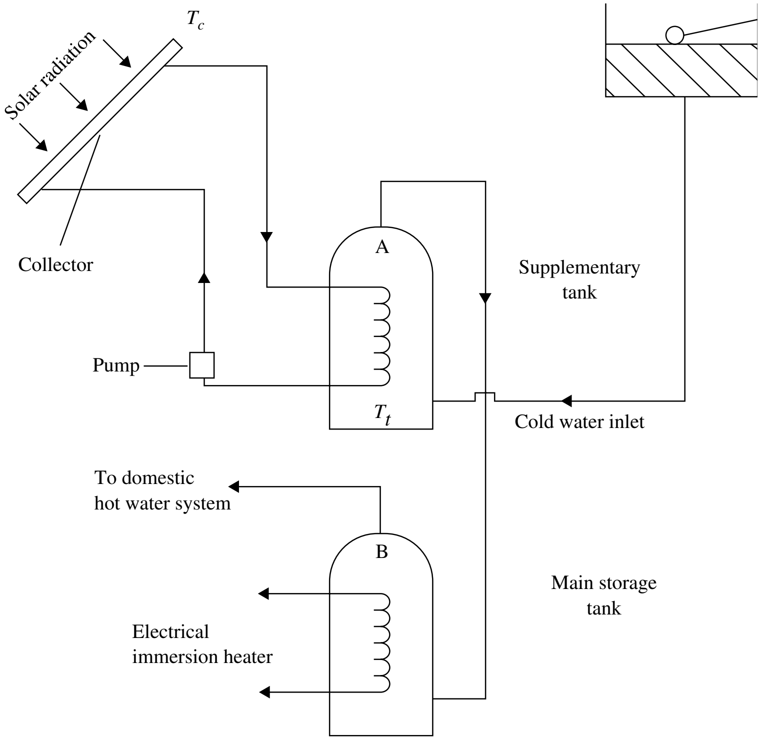


Fig. 11.16. Domestic (indirect) solar collector system [1].

installations, with roof-mounted storage tanks and inclined flat-plate collectors, that rely upon thermosyphon circulation.

A typical installation on UK domestic premises requires 1 square metre of collector area plus about 10 gallons (45.4 litres) of storage for each person in the household. The supplementary storage tank would normally be of capacity 30–50 imperial gallons, which is the same size as the standard storage cylinder tank of a UK domestic hot water central heating system. The two storage tanks of an indirect system do not need to be located in adjacent spaces. The main storage tank is likely to be in a clothes-airing cupboard. In many cases it is found convenient to locate the supplementary storage tank out of sight, in (say) a building roof space. The supplementary tank and its pipework must be well clad (i.e. lagged) to prevent heat loss [7].

Commercial solar water heating systems are expensive to install in Western countries. An installation for a typical dwelling house in the UK or USA would cost several thousand pounds sterling or several thousand US dollars. A closely considered cost–benefit analysis should first be undertaken to ensure that the "payback period" is acceptable. It is likely that the entire installation cost would need to be paid "up front". The customer has to choose either the loss of capital and interest from savings or, more expensively, borrowing money at commercial rates [8, 9]. Customers like short payback periods of less than five years.

In order to be economically viable, a domestic installation in the UK would need to be in the southern part of the country and in a household that uses a lot of hot water. One might raise the issue as to whether an environmentally friendly government should offer tax incentives to citizens to use renewable energy. Or is it more important to protect the industries involved in fossil fuel extraction and use?

11.4.4. *Worked examples involving solar flat-plate collectors*

Example 11.1

A solar collector measures 2 m × 1 m and has a capacity of 5 imperial gallons. After exposure to sunlight for 1 hour the mean temperature rise of the static water was 11.5°C. During this exposure of the solar collector a solarimeter was found to record the mean voltage $V = 4.5$ mV.

(a) Calculate the heat energy absorbed by the water.
(b) What is the rating in watts of an electric lamp, equivalent to the energy absorbed?
(c) Calculate the heat energy falling on the collector if the solarimeter calibration in $\mathrm{W/m^2}$ is 78 times the solarimeter voltage in mV.
(d) What is the efficiency of the collector under these conditions?

(a) An imperial gallon of water weighs 10 lb.

$$\begin{aligned}\text{Quantity of heat } Q &= \text{Mass of water} \times \text{temp rise} \times \text{specific heat}\\ \text{Mass} &= 5 \times 10 \times 454 \text{ g}\\ Q &= 5 \times 10 \times 454 \times 11.5 \times 1\\ &= 261{,}058 \text{ calories}\end{aligned}$$

By Joule's law

$$\begin{aligned}\text{Heat energy } W &= 4.2Q\\ &= 4.2 \times 261{,}058 \text{ joules}\\ &= 1{,}096{,}444 \text{ joules}\end{aligned}$$

(b)

$$\text{Power} = \frac{\text{energy}}{\text{time}} = \frac{1{,}096{,}444}{1 \times 60 \times 60} = 304.6 \text{ W}$$

(c)

$$\text{Input power} = 78 \times 4.5\ \text{W/m}^2$$

$$= 78 \times 4.5 \times 2 = 702\ \text{W}$$

$$\text{Input energy} = 702 \times 3600 = 2{,}527{,}200\ \text{joules in 1 hour}$$

(d)

$$\text{Efficiency } \eta = \frac{304.6}{702} = \frac{1{,}096{,}444}{2{,}527{,}200} = 43.3\%$$

which is a typical value.

Example 11.2

A flat-plate solar collector feeds a storage tank of capacity 50 imperial gallons (227 litres). The flow rate of the pumped water is 20×10^{-6} cubic metres per second. The ambient air temperature is 15°C. For 6 hours of operation the temperature rise of the collector water averages 22°C. If the temperature rise in the storage tank is 16.5°C, what is the system thermal efficiency? What is the power rating of the collector?

$$\text{Volume of water transferred} = \frac{20}{10^6} \times 6 \times 3600\ \text{m}^3$$

$$= \frac{20}{10^6} \times 6 \times 3600 \times 10^6\ \text{cm}^3$$

$$\text{Mass of water transferred } (1\ \text{g} \equiv 1\ \text{cm}^3) = \frac{20}{10^6} \times 6 \times 3600 \times 10^6\ \text{g}$$

$$\text{Quantity of heat} = \text{mass} \times \text{temp rise} \times \text{specific heat}$$

$$= \frac{20}{10^6} \times 6 \times 3600 \times 10^6 \times 22 \times 1$$

$$= 9.504 \times 10^6\ \text{cal}$$

$$\text{Heat energy collected} = 4.2Q = 4.2 \times 9.504 \times 10^6$$

$$= 39.91 \times 10^6\ \text{joules}$$

Energy transferred to storage tank, at a system efficiency $X\%$

$$= X/100 \times 39.91 \times 10^6\ \text{joules}$$

$$\text{Capacity of storage tank} = 227\ \text{litres} = 227\ \text{kg}$$

$$= 227{,}000\ \text{cm}^3$$

Amount of heat needed to raise tank temperature by 16.5°C

$$= 227{,}000 \times 16.5$$

$$= 3.745 \times 10^6 \text{ cal}$$

$$\text{Efficiency of collector system} = \frac{\text{heat transferred to tank}}{\text{heat collected}}$$

$$= \frac{3.745 \times 10^6}{9.504 \times 10^6} = 39.4\%$$

$$\text{Power rating of collector} = \frac{\text{energy collected}}{\text{time of collection}}$$

$$= \frac{39.91 \times 10^6}{6 \times 3600} = 1848 \text{ watts}$$

Example 11.3

(a) A glass-covered, thermally insulated, flat-plate solar collector is used to heat the water indirectly in a domestic storage tank of 50 imperial gallons (227 litres) capacity. Water is pumped through the collector at 20×10^{-6} m^3/s on a warm, sunny day when the mean temperature difference between the inflow and outflow is 17°C. If the effective area of the collector is 3 m^2 and it is 50% efficient, what is the temperature rise of the water in the storage tank after 4 hours? What is the power rating per unit area of the solar collector?

(b) If the efficiency of the collector system in part (a) above is reduced to 42%, what water flow rate would be needed to cause the same temperature rise in the storage tank?

(a) Mass of water through the collector in 4 hours

$$= \frac{20}{10^6} \times 10^6 \times 4 \times 3600 \text{ g}$$

Heat transferred to collector water

$$= \frac{20}{10^6} \cdot 10^6 \cdot 4 \cdot 3600 \cdot 17$$

$$= 4{,}896{,}000 \text{ cal}$$

$$\text{Energy collected in 4 hours} = 4{,}896{,}000 \times 4.2 = 20{,}563{,}000 \text{ joules}$$

Energy transferred to storage tank

$$= 50\% \text{ of energy collected}$$

$$= 10{,}281{,}000 \text{ joules}$$

$$\text{Mass of water in storage tank} = 50\ \text{gal} = 227\ \text{litres} = 227\ \text{kg}$$

$$\text{Temperature rise of storage tank} = \frac{\text{heat transferred from collector to storage}}{\text{mass of water}}$$

$$= \frac{\frac{1}{2}\cdot 4{,}896{,}000}{227{,}000} = 10.8^\circ\text{C}$$

$$\text{Power rating of collector} = \frac{\text{energy collected}}{\text{time of collection}} = \frac{20{,}563{,}000}{4\times 3600}$$

$$= 1428\ \text{W} = \frac{1428}{3} = 476\ \text{W/m}^2$$

(b) If the temperature rise of the storage tank is fixed, so is the ratio heat transferred/mass of water. If the heat transferred is reduced by a factor 42/50, the mass of water (i.e. pumping rate) must be increased by the same factor.

$$\text{New flow rate} = \frac{50}{42}\times 20\times 10^{-6}\ \text{m}^3/\text{s}$$

$$= 23.81\times 10^{-6}\ \text{m}^3/\text{s}$$

11.5. Solar Water Heating (Industrial)

Many industrial processes involve the conversion of water into steam and thence into mechanical work. This requires operating temperatures much higher than those achievable by flat-plate collectors. For instance, electrical power generation requires fluids of temperatures 120–320°C (250–600°F). To realise such high temperatures by solar heating it is necessary to use various forms of concentrator systems. Curved reflectors or lenses can be used to concentrate the solar radiation from a large collector area onto a smaller absorber area. Flat-plate solar collectors are inadequate by themselves but sometimes are incorporated to provide a level of pre-heating [10].

A maximum amount of energy can be collected if some form of solar tracking system is used. Various collector dishes or reflectors are driven by small electric motors so that they track the sun across the sky during daylight hours. This involves an elaborate computer-controlled tracking system that is expensive. Such systems are not commercially viable at present but many exist as experimental prototypes in different countries.

In order to provide some measure of effectiveness of solar concentrator systems, the term "concentration ratio" (CR) is used.

$$\text{Concentration ratio} = \frac{\text{collector area}}{\text{absorber area}} \tag{11.6}$$

In existing systems ratios in the range of 10:1 to 10000:1 are generally realised. As discussed in Sec. 11.4.2, a flat-plate solar collector does not normally incorporate any form of radiation concentration so that its concentration ratio is unity.

11.5.1. *Solar tracking systems*

11.5.1.1. *Parabolic dish collector*

A highly effective solar collector has the arrangement of a paraboloid-shaped dish, with the principle illustrated two-dimensionally in Fig. 11.17 [11]. The dish has to be mounted on a "ball and socket" type of joint because it must be able to swivel to any position and at any angle in order to track the sun. This involves moving the reflector through two degrees of freedom, or two axes of rotation, representing azimuth and elevation control. The absorber is fixed in position at the focus of the collector (reflector). With a large diameter reflector concentration ratios higher than 10000:1 can be realised. The parabolic dish collector uses largely direct radiation, rather than diffuse radiation. If the solar mirror is mounted on an equatorial (like an astronomical telescope) the drive motor needs only one degree of freedom.

11.5.1.2. *Solar power tower*

An alternative to the single collector system of Fig. 11.17 is to use a system of tracking mirrors or heliostats which focus the radiation to a fixed point. The principle is illustrated in Fig. 11.18 [12]. The redirected radiation absorbed by the receiver is converted to heat and used to vaporise a circulating heat transfer fluid. The resulting high temperature, high pressure fluid (usually a gas) can be used to drive an electrical turbine-generator unit. Fluids such as water, gas, molten salt or liquid sodium have been considered.

Very high temperatures can be realised with the upper theoretical limit set by the source temperature (5800 K). In practice a working limit of about 4000°C can be achieved using a tracking system. But in order to produce steam for conventional electricity-generating plants, a temperature of 600°C is adequate for the concentrated collector fluid. The high temperature furnaces of tracking systems have been used for the smelting of metals [12]. Solar thermal electricity generation can be realised in some locations by non-tracking systems.

Experimental heliostat power plants exist in several parts of the world. Felix Trombe of France was the pioneer in developing large solar furnaces [13]. The best-known of these is a 1 MW unit at Odeillo in southern France which uses 63 tracking heliostats covering an area of 2835 m^2. The peak solar flux at the focus of the parabolic reflector is about 16×10^6 W/m^2, representing a concentration ratio of about 16,000 times the standard insolation of 1000 W/m^2.

The principal heat loss from a heliostat power plant is the radiant losses from the absorber which are given by

$$P = A\epsilon\tau T^4 \tag{11.7}$$

where

P = heat power loss, W
A = absorber area, m^2
ϵ = emissivity, which is dimensionless
T = absolute temperature, K
τ = Stefan–Boltzmann constant, of value $5.67 \times 10^{-8}\ \mathrm{W/m^2 \cdot K^4}$

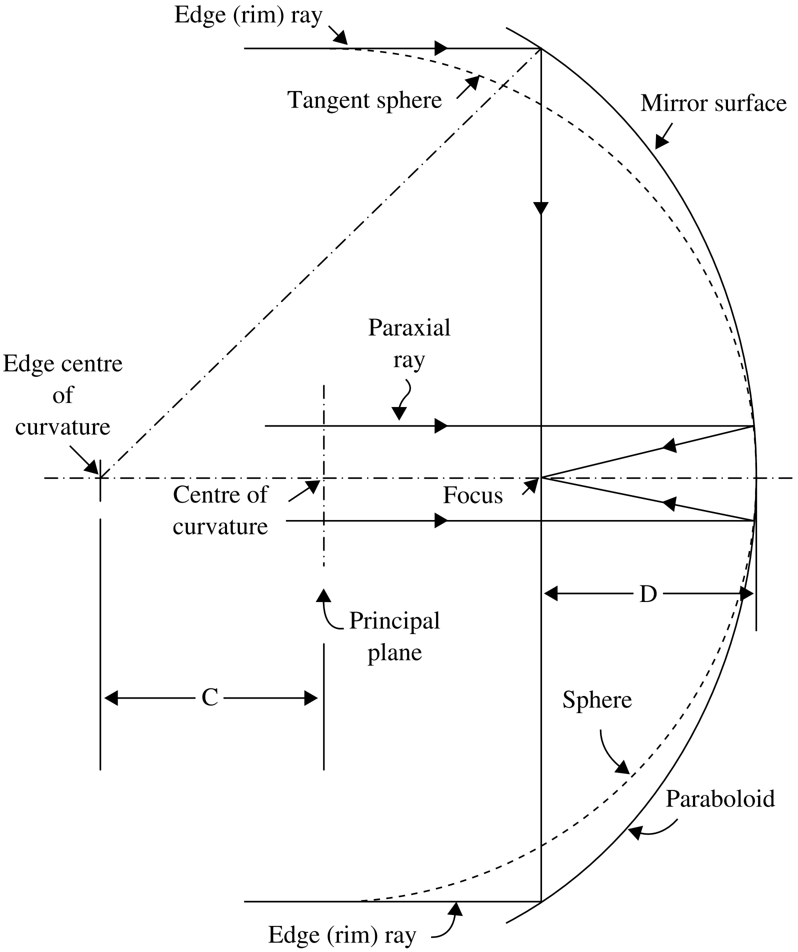

Edge (rim) ray
Tangent sphere
Mirror surface
Paraxial ray
Edge centre of curvature
Centre of curvature
Focus
D
Principal plane
C
Sphere
Paraboloid
Edge (rim) ray

Fig. 11.17. Principle of the solar parabolic reflector-concentrator [4].

The emissivity is the ratio of radiation emitted by a surface compared with the ideal value predicted by Planck's law. An ideal absorber is totally absorbent and has an emissivity of zero. An ideal reflector surface has an emissivity of unity since all the radiation is re-radiated. In practice, a good mirrored surface might reflect 98% of the input energy while absorbing 2%. A good absorber surface will, by comparison, absorb 98% of the input energy while reflecting only 2% [14].

Practical absorber surfaces have emissivity values of the order $\epsilon = 0.05$ (i.e. 95% of the input energy is absorbed and 5% is re-radiated).

The emittance characteristics of Fig. 11.14 confirm the relationship (11.7) that $P \propto T^4$ at constant wavelength.

From (11.6) the necessary absorber area A varies inversely with the concentration ratio, CR.

$$A \propto 1/CR \tag{11.8}$$

A high value of CR therefore permits a smaller absorber area and reduced re-radiation losses. Absorber design is a compromise between the concentration ratio, which is desired to be large, and absorber losses which are desired to be a minimum. The working temperature of the absorber is seen in (11.7) to be the dominant variable in the re-radiation power loss.

Many experimental systems are under investigation in the USA. Flat (or nearly flat) heliostat tracking mirrors are arranged in a 360° array around a central collector tower. The best-known of these is a 10 $\mathrm{MW_e}$ electrical generating plant near Barstow in the Mojave desert of southern California, Fig. 11.19. The 91-m-high

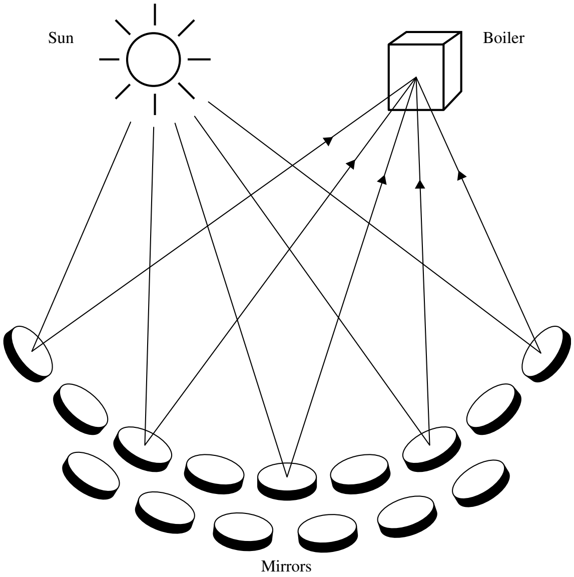


Fig. 11.18. Array of solar tracking reflector mirrors [12].

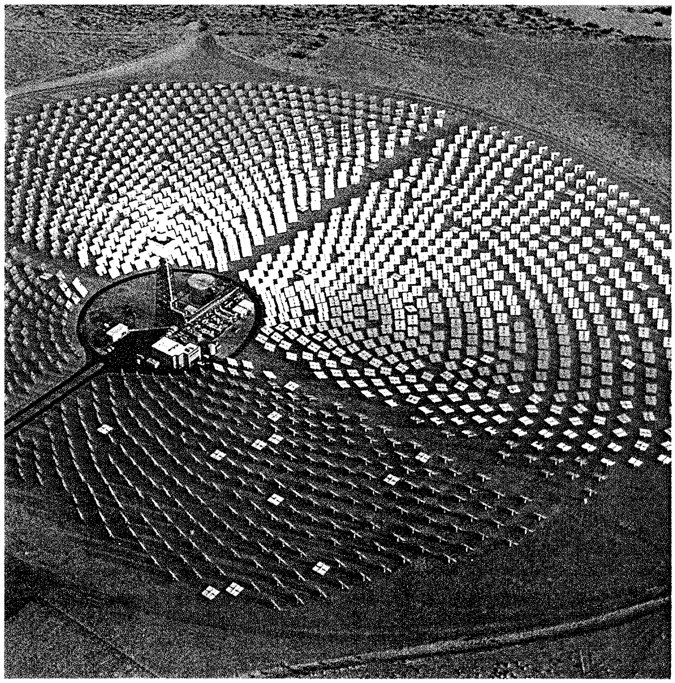


Fig. 11.19. 10 MW solar power plant, Barstow, California, USA.

tower uses the concentrated heat to boil water which is converted to high pressure steam at 560°C. Any surplus steam is stored for later use. The collector field consists of 1818 slightly concave heliostats with a total reflecting area of 72,538 m^2.

The amount of useful heat power from a solar tower can be expressed as

$$\begin{aligned} P &= I_D \cdot A \cdot \epsilon_H \cdot \eta_S \cdot \eta_{\text{real}} \\ &= I_D \cdot A_H \cdot \eta_S \cdot \eta_{\text{real}} \end{aligned} \tag{11.9}$$

where

I_D = direct solar radiation (W/m^2)

A_H = area of heliostat collectors

= actual ground contour of heliostat site (A) × fraction of the ground covered by heliostats (ϵ_H)

or

$$A_H = A\epsilon_H \tag{11.10}$$

$$\begin{aligned} \eta_S &= \frac{\text{incident energy converted into heat}}{\text{total energy incident on heliostats}} \\ &= \text{typical design value of } 0.53 \end{aligned} \tag{11.11}$$

Now, from Sec. 1.7.4 of Chapter 1, it can be seen that

$$\begin{aligned}\eta_{\text{Carn}} &= \text{Carnot efficiency of an ideal (i.e. lossless) heat–work cycle}\\ &= \frac{T_2 - T_1}{T_2} \qquad (11.12)\end{aligned}$$

where T_2 is the working fluid temperature, and T_1 is the dump or sink temperature, both in K.

$$\begin{aligned}\eta_{\text{real}} &= \text{realistic proportion of the ideal Carnot efficiency}\\ &\quad\ \text{(increases with working fluid temperature)}\\ &= \text{usually in the range 0.4–0.7} \times \eta_{\text{Carn}}\\ &= (0.4 - 0.7)\left[\frac{T_2 - T_1}{T_2}\right] \qquad (11.13)\end{aligned}$$

A numerical example incorporating equation (11.9) is given as Example 11.5 in Sec. 11.5.3 below.

The initial cost of a large-scale heliostat-power tower is very large in terms of money, raw materials and land. To generate 100 MW_e would require about a square mile of land. The installation would use 30,000–40,000 tons of steel, 5000 tons of glass and 200,000 tons of concrete — several times the raw material demand of a fossil fuel or nuclear station of the same capacity. Mining and manufacturing the steel, glass and concrete would produce air pollutants — notably sulphur and nitrogen oxides, carbon monoxide and particulates — equivalent to one year of effluent from an equivalent coal-burning plant [14]. Nevertheless, the longer term accounting in financial and environmental terms is greatly in favour of solar power rather than in terms of fossil fuels.

11.5.1.3. *Linear focus collectors*

There is a range of solar concentrator designs, known as distributed systems, in which the radiation is concentrated not at a point but along a length of absorber. In the parabolic trough collector, Fig. 11.20, the heated fluid, at a temperature in the range 100–500°C, is pumped along the pipe that is placed at the focus of the reflector [10]. Concentration ratios for this design of collector are much more modest than for the point concentrators of the previous section and are typically in the range $10 \leq CR \leq 100$. An alternative form of linear focus concentrator, having the same sort of performance, is shown in Fig. 11.21 [4].

If the axes of these collectors are horizontal in the east–west direction, they can be made to track continuously or be adjusted manually every few days. On the other hand, the axes may be oriented in the north–south direction at an optimum tilt for the particular latitude and continuous tracking is needed.

Adjustment of the parabolic mirror on the faceted mirror collectors of linear focus systems needs to take place only in the plane perpendicular to the collector tube. This represents only one degree of freedom compared with the two degrees

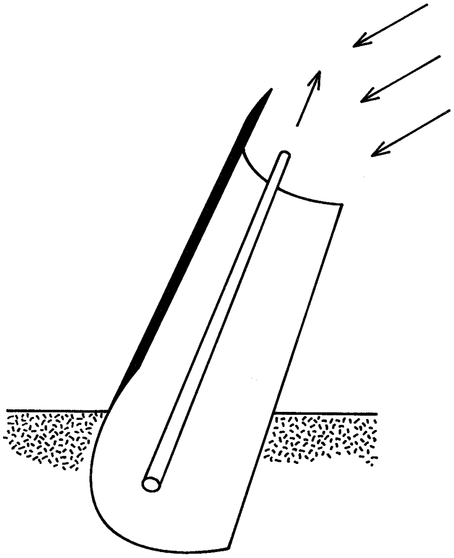


Fig. 11.20. Parabolic trough collector [11].

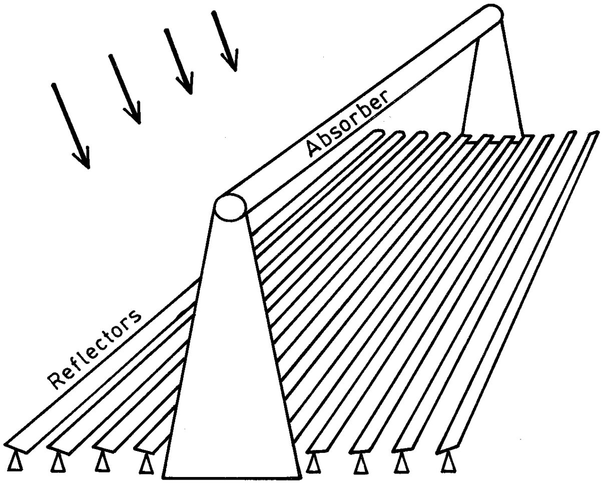


Fig. 11.21. Linear focus concentrator [4].

of freedom of, for example, solar power tower collectors. An alternative form of description is to say that the collectors in Figs. 11.20 and 11.21 have only one axis of tracking rotation whereas those in Figs. 11.18 and 11.19 have two axes of rotation.

The collector area of a linear focus type of collector is typically a few square metres. In order to provide a power output of 100 MW_e, equivalent to a solar power tower, several thousand modules would be required and a distributed collector system is not then practicable. If thermal losses at high working temperatures are minimised, distributed systems operate at about 60% efficiency in the characteristics of Fig. 11.15.

11.5.2. *Solar non-tracking systems*

One of the features of modern research in solar thermal systems is the search for effective non-tracking techniques. This represents an obvious saving of first cost and reduction of system complexity. Elimination of the need for an electrical supply also makes non-tracking systems suitable for remote locations. Recently developed forms of non-tracking collector can achieve temperatures in excess of 100°C, which is suitable in industrial process heating and can be applied to solar cooling.

11.5.2.1. *Evacuated tube collectors*

In the evacuated tube collector an inner absorber tube with a selective surface coating is surrounded by an evacuated glass tube, Fig. 11.22 [11]. The vacuum cavity reduces conduction and convection losses. Like a flat-plate solar collector, the tube collector can absorb both direct and diffuse radiation. A liquid or gas may be used as the heat transfer medium, flowing inside the inner absorber tube. The focussing element of the mounting does not play a major role in the operation. Commercially available versions of this type of collector have typical values 0.8 $\mathrm{W/m^{2\circ}C}$ for heat loss coefficient U and 0.84–0.86 for the transmittance-absorbance product $\tau\alpha$.

11.5.2.2. *Compound parabolic concentrator*

The compound parabolic concentrator developed by Winston in the USA has a cross-section like a parabola with its bottom end truncated [11, 16]. The two walls of the collector Fig. 11.23 are each part of different but equal paraboloids. The left-hand wall of the collector is part of a parabola with its focus at point D, which is at the base of the right-hand collector wall. Similarly, the right-hand collector wall has its focus at point C. With appropriate dimensioning all the incoming radiation can be concentrated near the base and used to irradiate a thermionic or photovoltaic collector. If the design is such that points C and D are coincident, all of the radiation can be concentrated along the base line, with a concentration ratio of about 10:1.

11.5.3. *Worked examples involving solar thermionic concentrator systems*

Example 11.4

A flat-plate solar collector feeds a storage tank of capacity 50 imperial gallons (227 litres). The flow rate of the pumped water is 20×10^{-6} $\mathrm{m^3/s}$. The ambient temperature is 15°C and the temperature rise of the collector water is 22°C for

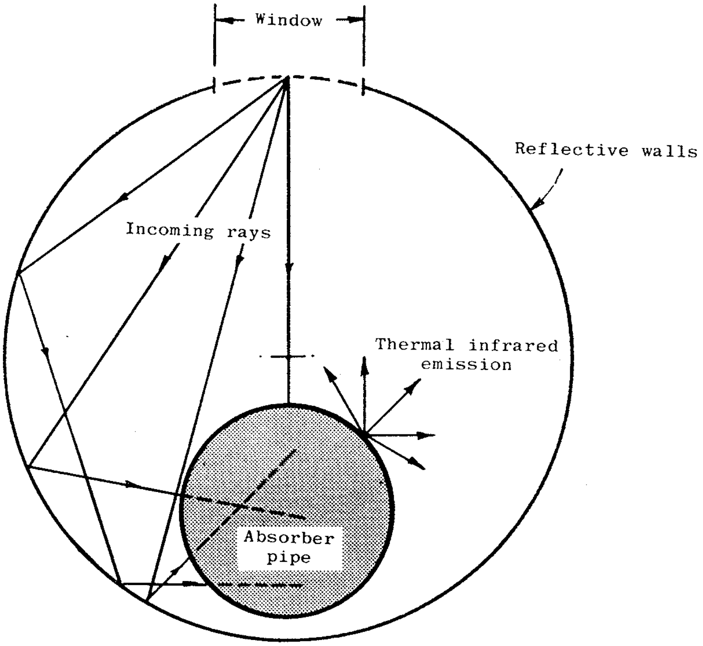

Window
Reflective walls
Incoming rays
Thermal infrared emission
Absorber pipe

Fig. 11.22. Optical cavity absorber [11].

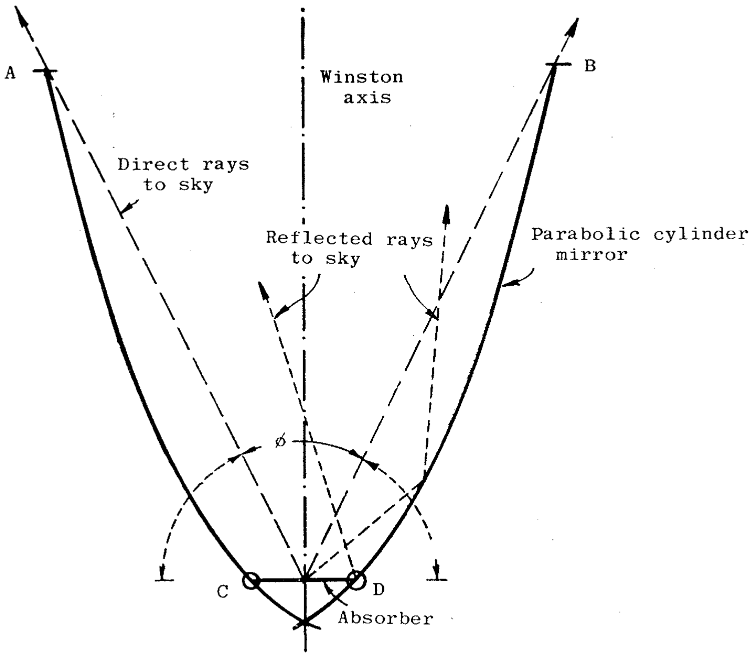

A
B
Winston axis
Direct rays to sky
Reflected rays to sky
Parabolic cylinder mirror
ø
C
D
Absorber

Fig. 11.23. Basis of the compound parabolic concentrator [16].

6 hours. If the temperature rise in the storage tank is 16.5°C, what is the thermal efficiency? What is the power rating of the collector? Calculate the Carnot efficiency of the collector and hence estimate the overall efficiency of converting the collector heat gain into mechanical work.

The calculations referring to the thermal operation of this particular plate collector are given in Worked Example 11.2 in Sec. 11.4.4. Relevant values were calculated as

$$\text{Thermal efficiency } \eta_{\text{thermal}} = 39.4\%$$
$$\text{Power rating of the collector} = 1848 \text{ watts}$$

The Carnot efficiency for an ideal heat–work exchange cycle is defined by (11.12).

$$\eta_{\text{Carn}} = \frac{T_2 - T_1}{T_2} = \frac{22}{273 + 22} = \frac{22}{295} = 7.46\%$$

The low value for η_{Carn} is typical of lower temperature systems. A multiplier is now used to represent the realistic proportion of the Carnot ideal efficiency that is obtained in practical energy transfer from heat to mechanical work systems, (11.13).

$$\eta_{\text{real}} = (0.4 - 0.7) \times \eta_{\text{Carn}}$$

For flat-plate solar systems the lower value of 0.4 is appropriate. The overall efficiency in using this flat-plate collector as a power source to produce mechanical work is therefore

$$\begin{aligned}\eta_{\text{overall}} &= \eta_{\text{thermal}} \times 0.4 \times \eta_{\text{Carn}}\\ &= 0.394 \times 0.4 \times 0.0746 = 1.18\%\end{aligned}$$

The very low value of overall efficiency is typical and demonstrates that the flat-plate solar collector is completely unsuitable as a power source to produce mechanical work. This is largely due to the relatively low working temperature. In order to produce mechanical energy, with an acceptable level of efficiency, it is necessary to use solar concentrator types of collector with much higher working fluid temperatures.

Example 11.5

A solar power tower plant receives an average direct component of concentrated incident radiation of 950 W/m^2. The conversion efficiency of the heliostats into thermal energy is 53%. The operating temperature of the fluid is 560°C and the sink temperature is 100°C. Calculate the area of heliostats and the land area required to generate 100 MW of thermal power.

The Carnot efficiency in this case is

$$\eta_{\text{Carn}} = \frac{560 - 100}{560 + 273} = \frac{460}{833} = 55.2\%$$

For a thermal plant working at 560°C the realisable thermal efficiency is taken as 70% of the ideal Carnot value

$$\eta_{\text{real}} = 0.7\eta_{\text{Carn}} = 0.7 \times 0.552 = 0.386$$

The conversion efficiency of the heliostats, η_S, defined in (11.11), is specified as

$$\eta_S = 0.53$$

In (11.9), I_D is given as 0.95 kW/m^2 so that

$$P = 0.95 \times 0.386 \times 0.53 \times A_H = 0.19A_H$$

where P is in kW when the heliostat area A_H is in square kilometres. In terms of the units of the present problem

$$P = 194A_H$$

where P is in MW and A_H is in square kilometres.

It is necessary to assume that the fractional value of ϵ_H in (11.10) is 1/4. In other words the heliostats occupy one quarter of the area of the ground contour A of the power plant site

$$A = \frac{A_H}{\epsilon_H} = 4A_H$$

The thermal power generated by the heliostats in this case can therefore be expressed as

$$P = \frac{194}{4}A = 48.5A$$

where P is in MW and A is in square kilometres of land.

To generate 100 MW of thermal power therefore requires a heliostat land site covering an area

$$A = \frac{100}{48.5} = 2.075 \text{ km}^2$$

If the corresponding land site was square it would have a side length of 1467 metres or about 1600 yards.

Example 11.6

A modern conventional power station can generate up to 2000 MW$_\text{e}$ of electrical power. If this amount of electrical power is to be obtained from a solar tower-heliostat facility, what is the approximate land area that would be required?

The thermal energy from the heliostats would need to be processed through steam turbines or gas turbines which are then used to rotate electrical generators. The station full load rating of 2000 MW_e is likely to be achieved using four 500 MW_e generators, of very high efficiency. Assume that

$$\eta_{\text{gen}} \approx 0.98$$

The associated turbines are likely to have an efficiency of the order

$$\eta_{\text{turbine}} \approx 0.5$$

To provide an electrical output of 2000 MW_e the thermal power input is therefore required to be

$$P_{\text{thermal input}} = \frac{2000}{0.5 \times 0.98} = 4082 \text{ MW}$$

In Example 11.5 it was found that a thermal output power of 100 MW required a land area of 2.075 km^2. With a solar furnace and (say) steam plant of the same thermal rating it is seen that the required land area A would be

$$A = \frac{2000}{100} \cdot 2.075 = 41.5 \text{ km}^2$$

Now

$$1 \text{ mile} = \frac{1760 \times 3}{3.281 \times 1000} = 1.609 \text{ km}$$

and

$$1 \text{ square mile} = 1.609^2 = 2.59 \text{ km}^2$$

Therefore

$$A = \frac{41.5}{2.59} = 16.02 \text{ square miles}$$

If the required site covered a square area the side length would be 4 miles. This is far more ambitious a scale of operation than anything that has so far been attempted, anywhere in the world.

11.6. Passive Solar Space Heating of Buildings

Solar radiation can be used directly to heat the air in buildings. In effect the whole building is then being used as a solar collector. If a house design is tuned to the local climate, then nature does most of the work. The passive solar approach operates on the principles of direct admission of the solar radiation, thermal insulation and heat storage, control of the heat gain, and with all of the heat energy input distributed by natural conduction, convection and radiation. This has the advantages of simplicity, reliability, durability and economy.

In all passive solar systems the architecture and structure of the building must be designed so that much of the input energy can be stored. This can be achieved using large masses of materials that have a high heat-retaining capacity, such as masonry, concrete, adobe, stone and water.

11.6.1. *Direct gain solar systems*

In so-called "direct gain" systems the incoming radiation directly heats the air space of the building and also contributes to the heat store. The process works best when the long axis of the building is oriented east–west and there is a large area of south-facing window (in the northern hemisphere). Only limited window area should be incorporated on the east and west walls.

The principle of one form of direct gain solar house is illustrated in Fig. 11.24 [17]. The wintertime sun is low in the sky and provides solar input through the south-facing windows. A rough estimate of the area of glazing required is to provide 1 square foot for each 4 square feet of floor area in the living accommodation. During the summer periods, when the sun is high in the sky, the overhangs prevent excessive radiation from entering. The use of a roof overhang to prevent excessive summer radiation is very ancient. Cliff dwellings have been discovered in Mesa Verde, Colorado, USA, dated about 1200–1300 AD, that were built to incorporate this principle.

In addition to directly heating the air in the building space, a lot of energy is absorbed into the walls and floors, which might be up to 1 foot in thickness. After dark this absorbed heat is radiated back into the building space and it is advisable to insulate the south-facing glazing to prevent too much heat loss by re-radiation. When the storage material receives direct radiation, a US design criterion is that at least 40 lb (18 kg) of storage water or 150 lb (68 kg) of rock or masonry

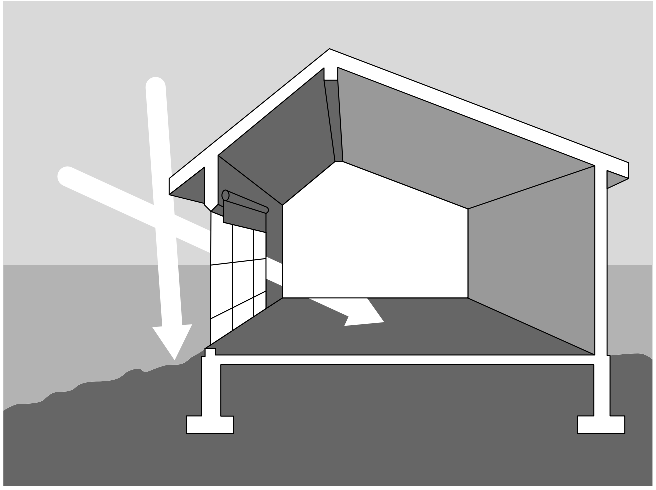


Fig. 11.24. Solar house with direct gain heating [17].

(not shown in Fig. 11.24) is required for each square foot of south-facing glazing. The thermal storage properties of some common materials are given in Table 11.7 [10].

One of the earliest and most successful direct gain passive solar buildings is St. George's County Secondary School in Wallasey, near Liverpool, England, which opened in 1965. This uses concrete floors and walls with an exterior wall insulation consisting of 13.5 cm of polystyrene. The south-facing wall is 8.2 m high and 70 m long, with mostly double glazing. All of the necessary heating is obtained from the solar input, lighting and the body heat of the students. Because of the massive thermal storage of the thick concrete, the temperature fluctuation is only 2–3°C. The structure of the building performs the equivalent function of the flywheel in rotating mechanical systems. Its thermal inertia tends to dampen any large temperature changes.

Direct gain houses of the type shown in Fig. 11.24 require adjustable window screens or blinds to prevent excessive solar input at certain times of the year. Even with the absorbtive capacity of the masonry, the air temperature can become uncomfortably warm. Two of the chief difficulties with direct gain systems are the glare from reflections inside the house and ultraviolet damage to the glass [10].

Table 11.7. Heat storage capacities of materials at room temperature.

Materials	Specific heat Btu/lb.F° cal/g C°	Density 1/ft^3	kg/m^3	Btu/ft^{3}F	Heat storage capacity kcal/m^{3}C
Water	0.999	62.3	998	62.2	997
Mild steel	0.12	489	7830	58.7	940
Silica	0.316	140	2240	44.2	709
Paraffin	0.69	56	899	38.6	620
Rock	0.21	165	2640	34.7	550
Concrete	0.23	140	2240	32.2	516
Chalk	0.215	143	2290	30.8	493
Asphalt	0.22	132	2120	29	465
Glass	0.18	154	2470	27.7	444
White oak	0.57	47	750	26.8	429
Building brick	0.2	123	1974	24.6	395
Sand	0.191	94.6	1520	18.1	290
Clay	0.22	63	1010	13.9	222
Cork, granulated	0.485	5.4	87	2.6	42
Polyurethane	0.38	1.5	24	0.6	9

Ref.: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. *ASHRAE Handbook of Fundamentals*, New York, USA, 1977

11.6.2. *Indirect gain solar systems*

11.6.2.1. *Thermal storage wall*

One alternative to direct gain systems is the use of a thermal storage wall. The best-known of these is the Trombe wall. A large concrete wall with a blackened outer surface is located immediately inside the south-facing double-glazed window, Fig. 11.25 [18]. The incoming radiation heats the air in the narrow cavity (i.e. 7–17 cm) between the wall and the window but is mostly absorbed by the wall. Heat absorbed by the wall causes the interior wall temperature to rise and to transfer heat energy into the house indirectly by conduction, convection and radiation. This usually involves a time delay of several hours so that the heat stored from the morning sun becomes available to heat the house in the evening. Some information

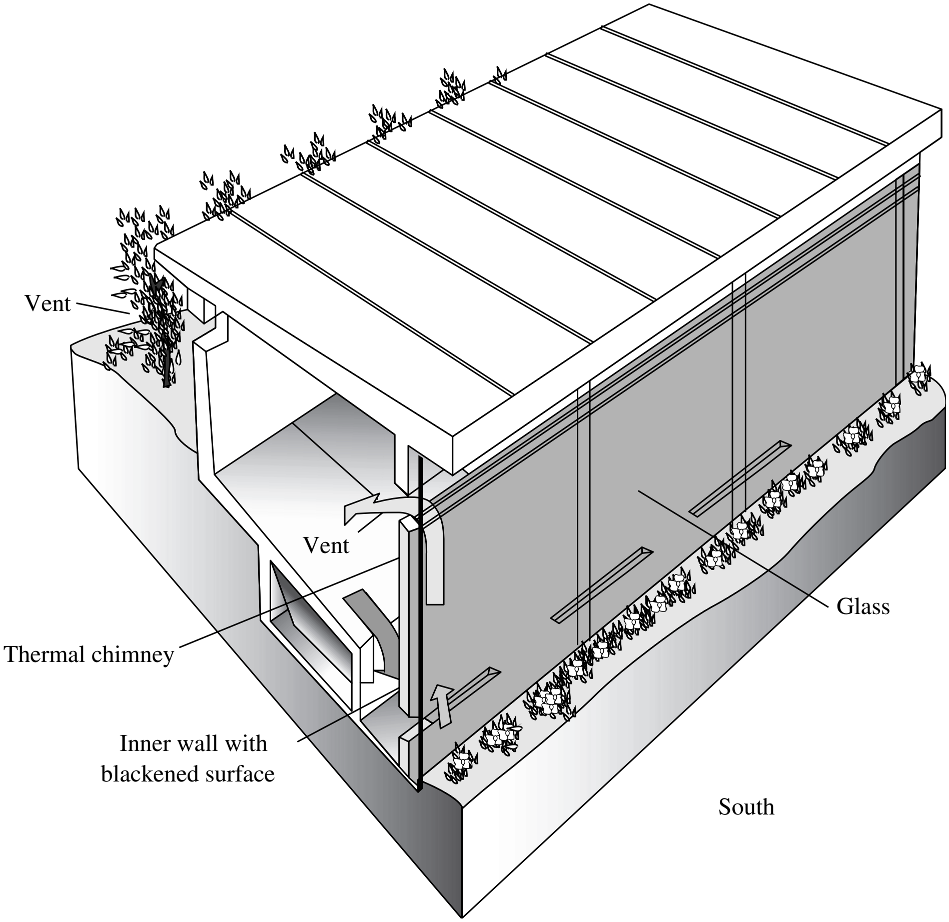


Fig. 11.25. French solar house incorporating a Trombe wall [18].

Table 11.8. Measured performance of a Trombe thermal storage wall.

Thickness (inches)	Temperature swing of the inside surface °F	°C	Time delay to achieve peak temperature on inside surface (hours)
8	40	22	6.8
12	20	11	9.3
16	10	5.5	11.9
20	5	3	14.5
24	2	1	17.1

Ref.: *Engineers' Guide to Solar Energy*
Y. Howell, J. A. Bereny
Solar Energy Information Services
Cal., USA, 1979

about the intrinsic time delay of operation of a Trombe wall is given in Table 11.8, which includes data on typical wall thicknesses.

If the wall is vented at the top and bottom, as in Fig. 11.25, the cavity heated air is circulated round the house by natural convection or by the use of a fan blower. This facilitates the daytime transfer of about 30% of the total input heat throughout the living space. The dark outer surface of a vented wall can reach a temperature of 160°F and an unvented cavity can reach 200°F. Nighttime re-radiation can be greatly reduced by the use of a screen across the wall window. The two vents should be closed at night to prevent warm air from the living space circulating through the wall-window cavity and being cooled by contact with the glazing.

Summertime cooling can be achieved by admitting air through north-facing windows and closing off the top vent of the Trombe wall. The cool air then passes through the house, up the cavity, and is expelled through an open window in the glazed south surface.

Trombe walls have the important disadvantages of high construction costs and reduction of the available space within the house. The important design features of a Trombe wall are the area, the thickness and the thermal conductivity. A high conductivity together with a high thermal storage capacity is desired. Materials that have poor thermal conductivity, such as wood, paper, plasterboard (gypsum), cork, cellulose, etc., are to be avoided [10].

The fraction of the total winter heating load that is obtained from the solar system is sometimes defined as the "solar fraction". Variation of the solar fraction versus wall thickness with thermal conductivity as parameter has the form shown in Fig. 11.26 [10]. The infinity line in Fig. 11.26 represents a water Trombe wall since the natural convection of heated water causes very rapid conductivity. It can be seen that in order to obtain maximum solar heating, a wall thickness between 8 and 16 inches is desired, using a material such as concrete that combines good conductivity with high storage capacity, as seen in Table 11.7. Too thin a wall would lack thermal inertia and would permit too great an internal temperature variation.

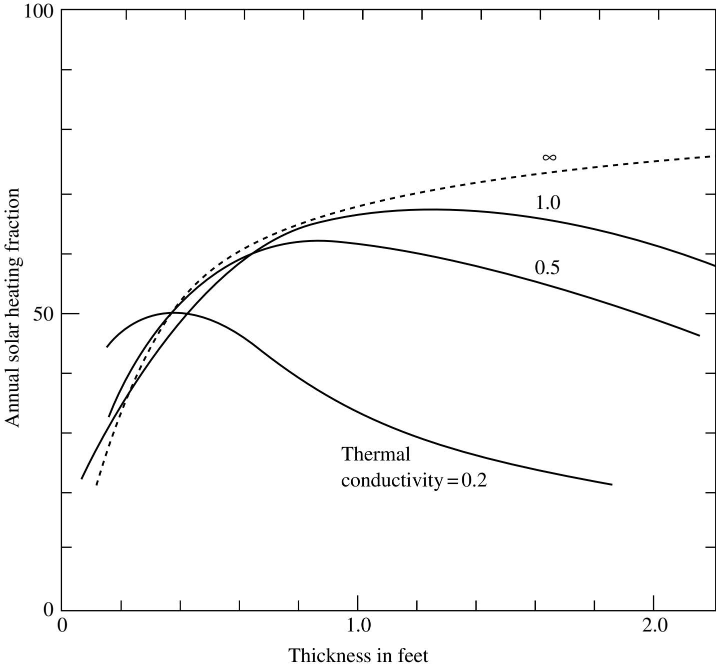


Fig. 11.26. Performance of a thermal storage wall (with thermal conductivity as parameter) [10].

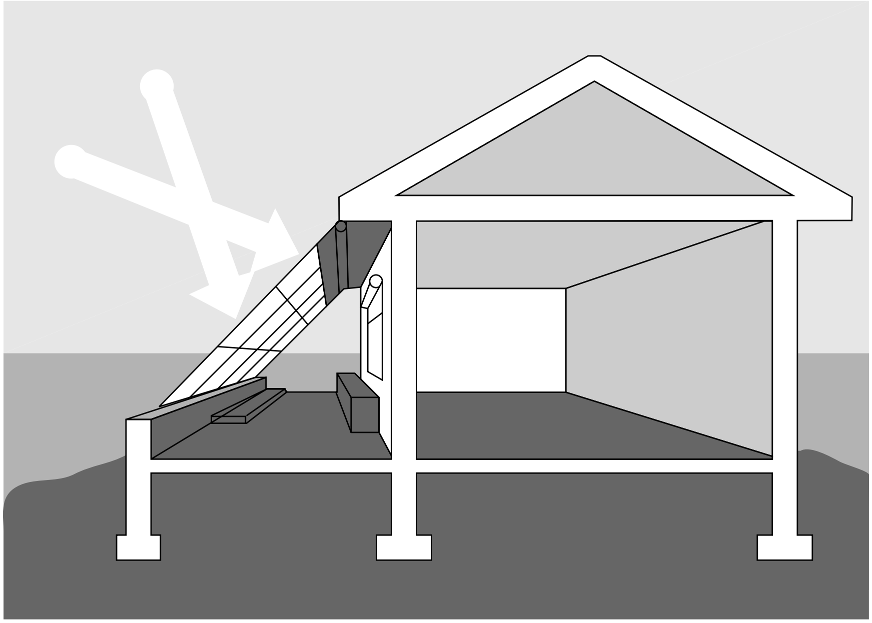


Fig. 11.27. Use of an attached sunspace [17].

11.6.2.2. *Solar greenhouse (sunspace)*

The benefits of direct gain radiation and indirect gain energy storage and transfer may be combined by the use of the solar greenhouse effect, Fig. 11.27 [17] and Fig. 11.28 [12]. The physical principle of the greenhouse effect is discussed in Sec. 11.4.1. Any excess heat collected in the sunspace can be stored in the thermal mass of the wall and used in the manner described in the preceding section.

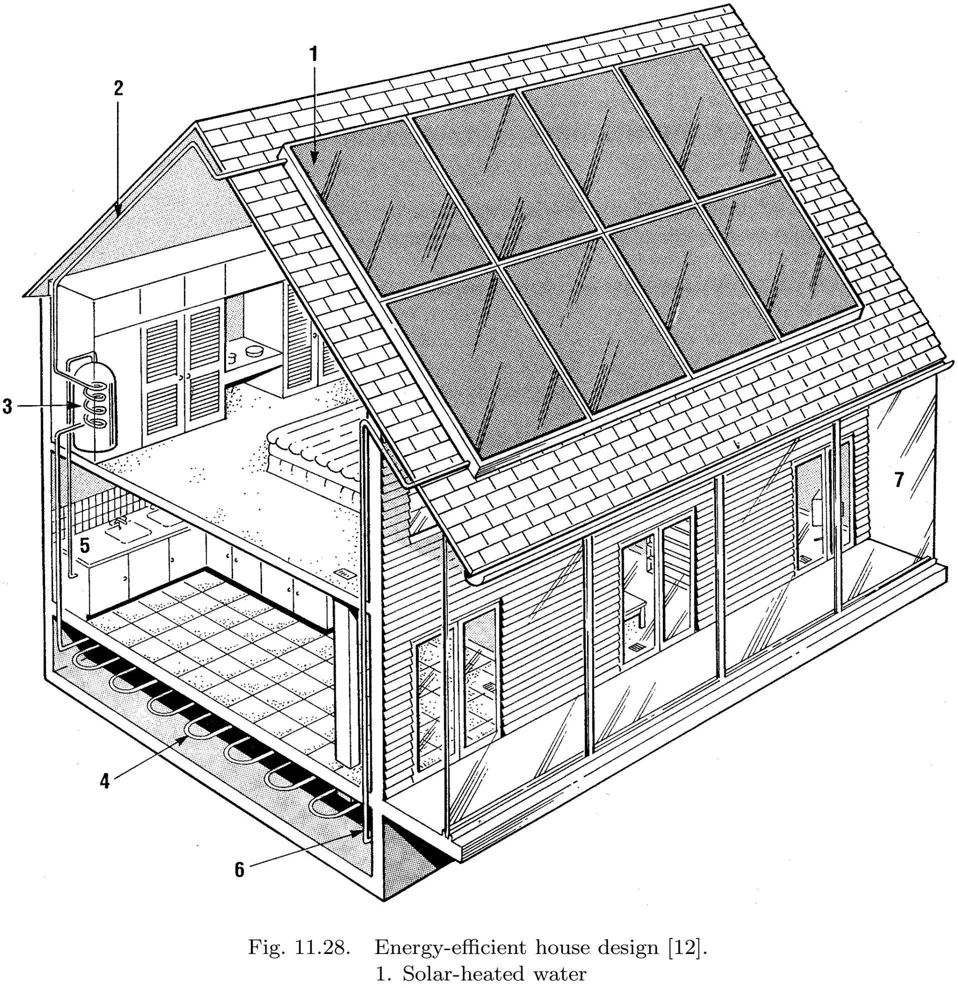


Fig. 11.28. Energy-efficient house design [12].
1. Solar-heated water
2, 3. Solar energy transferred to domestic water system
4. Underfloor heating
5. Domestic hot water
6. Solar water return pipe
7. Built-in greenhouse

11.6.2.3. *Roof pond*

A house with a flat roof can incorporate a roof pond of water contained in transparent plastic containers. In the winter months the water is exposed to the incoming daytime radiation and is covered with thermal insulation during nighttimes. The daytime heat energy input is then retained and used to supplement the house heating by radiation inwards from the metal roof. During summer months the opposite is true — in daylight hours the water pond is screened from incoming radiation. At night the insulation is rolled back and the water becomes cold by nighttime evaporation. This cold water absorbs heat from the building during the day and constitutes a form of daytime air-conditioning.

11.6.2.4. *Solar salt pond* [3]

In a pond of natural water, the water below the surface, heated by solar radiation, rises to the surface by convection currents. A solar pond contains concentrations of dissolved salts that gradually increase in concentration with depth. The bottom layer is highly saline, covering a blackened pond-bed. On top of the pond the water is less saline so that there is a gradual increase of water density with depth.

Solar radiation penetrates to the lowest (high density) region of the pond. Any rising convection currents are suppressed by the density gradient. Heat losses from the pond surface are lower than would be obtained with natural water. The bottom saline region acts as a solar collector and its temperature can rise to 200°F, which is sufficient to drive a turbine. Although there are daily fluctuations in the surface water temperature and the surrounding ambient temperature, the bottom saline basin temperature remains fairly constant so that it acts as a massive heat store.

Several experimental solar ponds have been developed in the Dead Sea region of Israel, the largest being of 5 MW rating. Much larger rated installations are planned in the USA. Solar ponds can operate continuously throughout the year and can provide peaks of "topping-up" power on demand.

11.7. Problems and Review Questions

Solar flat-plate collectors

11.1. A solar collector is mounted at an inclination of 45° to the horizontal. If the sun rises to an inclination of 54° above the horizon, what proportion of the radiation is then falling normally onto the collector?

11.2. A solar collector in northern England is mounted with its axis inclined at the latitude angle 54° to the horizontal. If the total annual radiation energy on a horizontal is 1000 kWh/m^2, divided equally between direct and diffuse components, what is the radiation received by the collector?

11.3. A solar thermal collector is mounted at an angle $\alpha = 39.5°$ to the horizontal. If the direct and diffuse components of the solar radiation are both of value 320 W/m^2, what is the total radiation?

11.4. What is a typical working efficiency for a flat-plate solar collector? Show mathematically how this efficiency is affected by an increase of the circulating fluid temperature.

11.5. Explain what is meant by the term "greenhouse effect" with regard to solar radiation. How is this effect utilised in the design of collectors for solar water heating?

What is a typical working efficiency of a flat-plate, solar, water heating system? How could this efficiency be increased?

11.6. Describe, using a diagram, the essential features of an arrangement to heat indirectly the water of a domestic hot-water system using a flat-plate solar collector. In a typical system the flat-plate collector is housed in a thermally insulated container with a glass cover, exposed to the radiation. Explain the action of the glass-fronted container.

11.7. Sketch the form of a solar collector system for pre-heating the water in a domestic dwelling. Where would you prefer to locate the supplementary water tank? How would you check if the system is working?

11.8. Explain the basic principles of operation of a flat-plate solar collector.

Sketch a scaled characteristic of efficiency versus operating temperature (above ambient) for a collector with a single glass window. Identify a typical working point. How would this characteristic be modified if double-glazing was introduced into the window?

11.9. Describe the main features of power loss in a flat-plate solar collector. How are these related to the terms of the general collector efficiency equation? Referring to this equation, explain how you would attempt to improve the collector performance.

11.10. A flat-plate solar collector, mounted at the latitude angle and south-facing, has an effective area of 2 m^2. Water is pumped through this collector at the rate 20×10^{-6} m^3/s and the mean temperature difference between the inflow and outflow is 18.4°C. The collector is used to heat indirectly the water in a storage tank of capacity 50 imperial gallons (227 litres) for 5 hours continuously. If the system operates at a typical efficiency, calculate the temperature rise in the storage tank. What is the power rating of the flat-plate collector in W/m^2?

11.11. A solar collector is to be mounted on the south-facing roof a dwelling house, feeding a storage tank with a capacity of 30 imperial gallons (136 litres). The circulating pump is to operate at the rate of 20×10^{-6} m^3/s. On a warm, sunny day the difference of water temperature between the inflow and outflow at the collector is typically 15.5°C and this difference exists for 6 hours. What is the operating efficiency of the system if the temperature of the water in the storage tank is increased by 20°C?

11.12. A solar collector is to be mounted on a south-facing roof, feeding a storage tank of capacity 200 litres. The circulating pump operates at 20×10^{-6} m^3/s. On a typical day the difference of water temperature between the collector output and input is 17.2°C and lasts for 6.8 hours. If the temperature of the water in the storage tank is increased by 13.75°, what is the thermal efficiency of the system?

11.13. It is proposed to use a roof-mounted solar water-heating system to supplement the energy input into a certain industrial process. The south-facing solar collector is to be used to heat indirectly the water in a storage tank of capacity 5000 imperial gallons (22,700 litres). Water can be pumped through the collector by a range of available water pumps. On a typical summer day, there are 5.6 hours of sunshine which causes an average temperature difference of 16.5°C between the inflow and outflow of the collector.

(a) If the anticipated efficiency of the system is 42.6%, what rate of water pump flow in m^3/s is needed to cause a temperature rise of 12°C in the storage tank?
(b) If this pump is used and the temperature of the storage tank becomes 14.5°C, what is the efficiency of the collector system?

11.14. A flat solar collector of area 2 m^2 has a water inflow temperature of 13.5°C and an outflow of 52°C while the incident radiation is constant at 900 W/m^2. Use the empirical relation (11.5) to calculate the approximate thermal efficiency.
What value of efficiency is indicated if $T_c = T_a$, and why is this efficiency indication wrong?

11.15. Give a broad specification for a solar water heating installation for a typical UK domestic dwelling (i.e. three-bedroom, semi-detached house) occupied by four persons. In particular, specify the necessary area of collector and the capacity of the supplementary water tank. The installed commercial cost is quoted at £3200. Estimate the pay-back period if the household is (i) a heavy user of hot water, (ii) a light user of hot water.

Solar concentrator systems

11.16. What are the main differences between the countries of northern Europe and those of the Middle East with regard to solar radiation? What are the chief obstacles to the widespread use of solar water heating in the two regions?

11.17. Industrial applications where heat is converted into mechanical work require working fluids of temperatures in the range 250–600°C (much higher temperatures than are realisable by solar flat-plate collectors). Why are such high temperature fluids needed?

11.18. Calculate the Carnot efficiency of a concentrated heat solar system in which the high temperature is 450° while the low temperature is 40°C.

11.19. The difference between the inflow and outflow fluid temperatures in a flat-plate solar collector is 20°C. Explain why this is completely unsuitable as an energy supply for a thermodynamic energy converter (e.g. a steam engine).

11.20. A heat collector for an ideal heat–work (Carnot) system has a constant ambient temperature. Show, mathematically, that increase of the working fluid temperature will increase the Carnot efficiency.

11.21. A solar collector with constant incident radiation has an efficiency given by

$$\eta = A - B(T_2 - T_1)$$

where T_2 is the collector outlet temperature and T_1 is the ambient temperature. If the heated water is used as a source for an ideal heat engine (i.e. operating on a Carnot cycle), show that the maximum system efficiency occurs when

$$BT_2^2 = T_1(A - BT_1)$$

Calculate the efficiency when $T_1 = 25°\text{C}$ if $A = 0.6$ and $B = 0.001$ [3].

11.22. Define the term "concentration ratio" (CR) for solar collectors. How is the CR related to the working temperature of the solar absorber? What is the value of the CR for a flat-plate solar water heater?

11.23. How is the thermal power developed by a solar power tower system related to:

(a) the area of the heliostats,
(b) the solar radiation,
(c) the thermal efficiency of the heliostats, and
(d) the Carnot efficiency?

11.24. The absorber of a solar concentrator system operates at 550°C. The collector receives 200 W/m^2 of input power. If the concentration ratio is 50 and the absorber emissivity, is 0.05, what proportion of the input power is re-radiated? [Hint: Use (11.7).]

11.25. A solar power tower plant receives an effective average radiation of 1000 W/m^2 from its concentrator collectors. The conversion efficiency of the collector heliostats into thermal energy is 53%. If the plant fluid operates at 600°C and the sink temperature is 100°C, calculate the area of heliostats and the land area required to generate 100 MW of thermal power.

11.26. Enumerate and briefly discuss the advantages and disadvantages of a proposed 100 MW heliostat-power tower facility.

11.27. One of the largest electricity generation stations, using fossil fuels, is now rated at 2000 $\mathrm{MW_e}$ and uses four 500 $\mathrm{MW_e}$ turbine-generator sets. Use the result of Problem 11.21 to estimate the ground area that would need to be occupied by a solar power tower-heliostat installation delivering the same electrical power. If such an installation proved to be technically feasible, what considerations would arise in the choice of a suitable site?

11.28. Is access to the sun a legal right? Suppose, for example, that the owner of a small processing plant had spent US$50,000 (or equivalent) on building a solar water heating system that incorporated an array of roof-mounted solar collectors. The owner of an adjacent property then proposes to erect a taller building nearby such that it would effectively screen the solar collectors from the sun and render them useless. Does the owner of the processing plant have any legal right of protest or redress?

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CHAPTER 12

SOLAR PHOTOVOLTAIC CONVERSION

12.1. Basic Features of Solar Cells and Solar Systems

Solar radiation can be converted into electrical energy directly, without any intermediate process at all, by the use of solar photovoltaic (PV) cells. These cells are usually fabricated as flat discs, up to a few inches in diameter. The advantages of this form of electricity generation, compared with thermal processes involving the Second Law of Thermodynamics, are considerable. Advantages of photovoltaic generation include [1, 2, 3]:

(a) There are no moving parts so that little maintenance is required;
(b) They utilise an infinitely renewable (compared with the human lifespan) and pollution-free power source;
(c) The cells are reliable and long-lasting, with no harmful waste products;
(d) There is no discernible health hazard;
(e) The cells are usually made of silicon, which is one of earth's most abundant and cheap materials;
(f) The cells can be used on site in remote locations, such as buoys anchored at sea, or spacecraft in orbit;
(g) They have a high power-to-weight ratio, which is required in aerospace applications;
(h) They are manufactured and researched in a highly developed, scientifically based, well-funded industry, so that continual improvement of performance can be expected.

With this list of advantages above one can understand the very large investment of time and effort that has been, and still is, devoted to solar cell development. If solar photovoltaic converters were available more cheaply they would completely change the whole scene of electricity generation for mass consumption. Unfortunately they still (2002) remain several times too expensive for mass use, but are viable for specialised applications such as spacecraft, isolated communication stations and certain defence needs.

In considering the cost of solar cells the term "peak watt" of power is used. This means that the cell is required to generate 1 watt of power when the solar insolation (i.e. solar power per unit area) is 1000 W/m^2. With a typical efficiency of 10%, 1 m^2 of cell array area would then generate 100 peak watts.

12.2. Cost of Solar Photovoltaic Electricity

The quoted cost of electricity from solar photovoltaic cells varies widely. In 1973 the cost was $300/peak watt. By 1977, due to vastly increased research, the cost had dropped to $15/peak watt, falling further to $10/peak watt in 1983. In the late 1980s the cost had fallen to $2–$3/peak watt [2]. The decreasing cost of PV modules and the worldwide growth in their use are illustrated in Fig. 12.1 [4]. During 2000 the global installed base of PV generation exceeded 1 GW (1000 MW) for the first time. The costs of PV systems now (2002) vary between US$6 and US$12 per watt, resulting in costs for PV-generated electricity from US$0.25/kWh to over US$1.0/kWh. At these cost levels PV has an economic advantage, for applications from rural households to telecom repeater stations, over batteries and engine-generator sets where mains electricity is unavailable [4].

In order to be competitive with conventional generation the cost of electricity delivered to consumers must now (2002) be around $0.07 per kWh in the USA and £0.07 per kWh in Great Britain. This energy cost corresponds to an installed cost

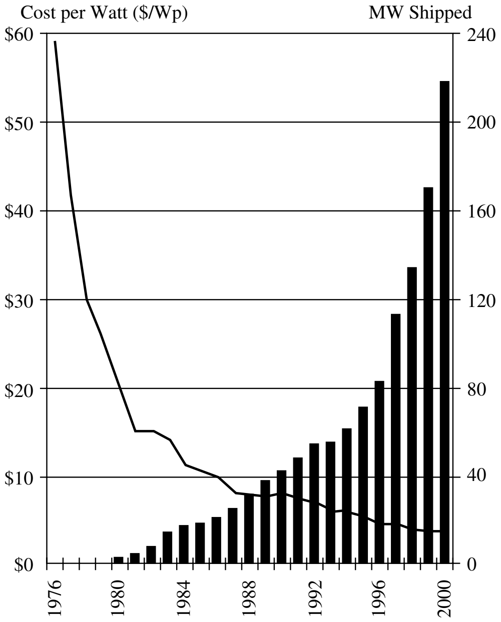


Fig. 12.1. Cost (US$/peak watt) and world production levels of photovoltaic modules [4].

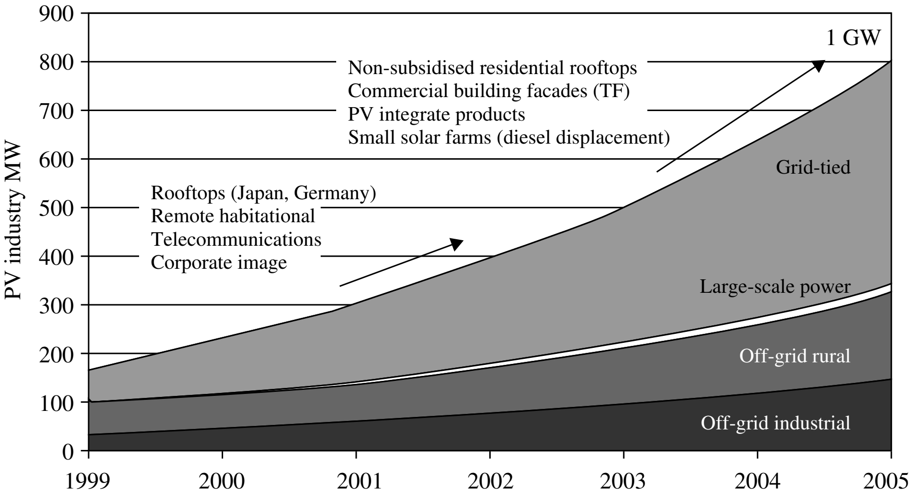


Fig. 12.2. Forecast market growth in the PV industry [5].

for solar cell arrays of \$0.15–\$0.3 per peak watt. When maintenance and interest upon capital costs are added (probably more than doubling the price per peak watt) the cost of solar-photovoltaic-generated electricity is found to be still several times the cost of conventional generation, using fossil fuels. A relevant numerical example is given as Example 12.9, in Sec. 12.8.

Figure 12.2 shows a forecast of the anticipated growth of PV market opportunities. Over 800 MW of new PV generation (equivalent to a large conventional power plant) is expected to be added each year. The largest area of growth is expected to be in grid-tied systems. Large scale PV power generation schemes will probably remain in the demonstration phase [4, 5].

12.3. Physical Nature of Semiconductor Materials [6]

Materials that are commonly used as semiconductors, such as silicon and germanium, are found to lie in the fourth column of the Periodic Table of Elements. The outer layer of electrons, sometimes called the valence shell, in the Bohr model of the atom consists of four electrons which enable a pure crystal of material to form tight covalent bonds. The nuclei consist of protons and neutrons summing to the respective atomic mass units. Quantum shells of electrons surround each nucleus so that the total number of electrons is equal to the atomic number and determines the place in the Periodic Table of Elements.

The covalent bonding in the lattice of a pure crystal is tight in that relatively much energy is necessary in order to free an electron from the bond and make it available for charge carrying. Pure semiconductor materials have such high resistivity that they are insulators at room temperature. The application of a voltage across a pure crystal of silicon or germanium, at room temperature, would cause only a small leakage current. For example, a potential difference of 100 volts across a cubic centimetre crystal of silicon would result in a leakage current of about 4 milliamperes.

To convert pure semiconductor material from a light-sensitive but grossly inefficient electricity converter into a form suitable for use in transistors or photovoltaic cells, capable of much higher current capacity, it is necessary to increase the conversion efficiency. This can be done by increasing the energy of the outer shell electrons. Such modification can be achieved by a very complex industrial process known as "doping", whereby other materials, lying in the third or fifth column of the Periodic Table, are combined with the pure semiconductor. This revolutionary breakthrough was pioneered at the Bell Telephone Laboratories in New Jersey, USA, in the 1950s.

12.3.1. *Group-3 (acceptor) impurities*

In the process of doping, atoms of a selected impurity material are substituted for some atoms of the pure semiconductor material within its semiconductor crystal lattice. Materials such as boron, aluminum, gallium and indium lie in the third column of the Periodic Table and are characterised by having three electrons in their outer shells. Incorporation of (say) a boron atom into a lattice of silicon atoms results in an effect that is depicted in Fig. 12.3(a). The impurity atom forms three covalent bonds with adjacent atoms. In the fourth side, however, no impurity electron is available to bond with the semiconductor electron and a "hole" appears in the location of the missing electron. Such incomplete bonding can be arranged to occur throughout the crystal. Group-3 or trivalent impurities are called acceptor impurities because they have the capability of accepting free electrons. The application of a potential difference across the crystal will cause a migration of holes.

Doping a pure semiconductor material with acceptor impurity forms a p-type (positive) semiconductor in which the holes are called majority carriers and the free electrons are called minority carriers.

12.3.2. *Group-5 (donor) impurities*

Materials such as arsenic, phosphorus and antimony lie in the fifth column of the Periodic Table and are characterised by having five electrons in their outer shells, available for chemical reactions. Incorporation of (say) a phosphorus atom into a lattice of germanium atoms results in an effect that is depicted in Fig. 12.3(b). The impurity atom forms four covalent bonds with adjacent atoms but one electron per phosphorus atom lies free in the valence shell. The free electron has relatively high energy and may be easily detached from its parent atom by the application of an emf to the crystal.

Group-5 or pentavalent impurities are called donor impurities because they have the capability of donating free electrons. Doping a pure semiconductor material with

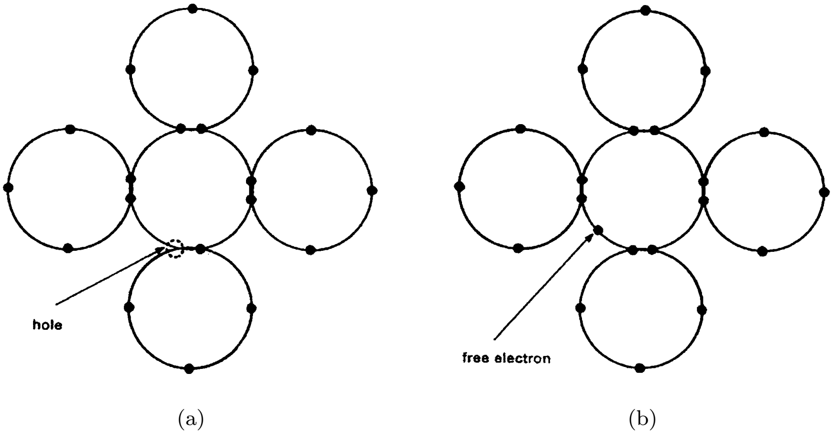


Fig. 12.3. Planar representation of doped semiconductor lattice: (a) acceptor impurity, (b) donor impurity (from [6]).

donor impurity forms an n-type (negative) semiconductor in which the electrons are called majority carriers and the holes are called minority carriers, which is the opposite way round from acceptor-impurity-doped material.

Because of doping, the high intrinsic resistivity of pure semiconductor materials is markedly reduced and doped materials are adequate conductors of electric current. In this book the term "semiconductor" should always be taken to mean the doped, commercially available materials now so abundantly used in the electronics industry.

12.4. Photovoltaic Materials

12.4.1. *Crystalline silicon (c–Si)*

Early forms of silicon photovoltaic cells were very expensive because of difficulties in the industrial preparation of sufficiently high-grade silicon. Very pure single crystals of silicon needed to be grown as cylindrical ingots, about 10 cm diameter, in order to maximise the cell exposure area. This is now known as "monocrystalline" silicon.

Processing and fabrication problems still exist in the preparation of single crystalline silicon cells, which remain very expensive. The wafers are typically 250–300 μm thick and need to be cut by diamond slitting discs of about the same thickness, which is both expensive and wasteful of the silicon material. Preparation of the pure crystals involves temperature control — within ±0.1°C of a melt at 1420°C. After cutting, grinding and polishing — all labour-intensive operations — the silicon wafers have to undergo a gaseous diffusion process involving the bonding of another material. One development that has been responsible for reduction in the cost of solar photovoltaic cell silicon is to grow the silicon crystal in the form of a ribbon rather than an ingot. By drawing the seed crystal upwards through a die in the molten silicon, a ribbon crystal several feet long may be obtained. Ribbon crystal material can now be made of thicknesses in the range 4–300 μm with much less stringent temperature control. The costly process of cutting thin wafers from large single-crystal cylindrical ingots is then eliminated. The ribbon process results in less pure silicon than the traditional method and produces cells with efficiencies of the order 10–12%.

Another development in the use of crystalline forms of silicon is the use of polycrystalline silicon rather than single-crystal material. Many small silicon crystals are oriented randomly within thin layers of polycrystalline material. This is much cheaper to produce than single-crystal forms and uses much less silicon material. Reported efficiencies with polycrystalline solar cells are only 5–7%.

12.4.2. *Amorphous (uncrystalline) silicon (a–Si)*

In amorphous silicon there is no regular crystal structure. The very expensive production techniques involving pure single-crystal forms are unnecessary. The absorption coefficient for amorphous silicon, in the visible light range, is more than ten times the value for single-crystal silicon. Amorphous silicon can be deposited onto backing material (sometimes called "substrates") in very thin films, of the order 1 μm thick. This greatly reduces the amount of silicon material used and, consequently, the cost of mass production.

Although presently available amorphous silicon solar cells are relatively cheap, their maximum efficiency is low, of the order 7–10%. This raises interesting cost-efficiency considerations in the design of any specific photovoltaic cell array. Amorphous silicon cells with an efficiency range 5–6% are to be used in a 50 MW photovoltaic power station to be built in the desert outside Los Angeles, California, USA [9].

Can it be anticipated that future generations of amorphous silicon cells will eventually achieve the same levels of operational efficiency as crystalline silicon cells? Although amorphous silicon (a–Si) modules have dominated the consumer electronics market since the 1980s, they are only currently (2002) being launched into the power market [7].

12.4.3. *Materials other than silicon*

In the search for more efficient solar photovoltaic cells many different semiconductor materials have been investigated. An historical perspective of the results is given in Fig. 12.4 [7]. The market is still dominated by crystalline silicon cells, with the most recent forms claiming efficiencies approaching 25%, which is higher than the historical maximum theoretical value. There is a 7–8% gap between the realised efficiencies of crystalline silicon cells and thin-film versions (the most economic) of other options, Fig. 12.4. Some of this loss is due to inhomogeneities in the polycrystalline materials but there is also an inherent mechanism, not yet (2002) identified, that reduces the efficiencies of CdTe and CIS materials [7]. Another way of interpreting Fig. 12.4 is that CdTe, CIS and other thin-film technologies (not shown) are about 20 years later in development than Si. But Si cells are now approaching the theoretical limit of their efficiency — will thin-film cells eventually catch up? A thin-film competitor, not shown in Fig. 12.4, is the gallium-arsenide (GaAs) cell, attractive because of its high efficiency. It will operate at temperatures up to 200°C, whereas the maximum working temperature for silicon, about 100°C, is already accompanied by a serious loss of efficiency. Because of the higher temperature tolerance, gallium arsenide cells can be used in focussing concentrator systems. Gallium arsenide cells, however, cost several times the price of silicon cells and it is questionable if the world supply of gallium would be adequate to facilitate its widespread mass use.

A recent development is to use multilayer cells, with different energy gaps, so that sunlight first strikes the material with the largest band gap. One recent design stacks layers of gallium arsenide onto layers of silicon. A GaAs cell on top absorbs solar energy from the blue (short wavelength, high energy) end of the spectrum, passing redder light to a silicon cell beneath. Higher conversion efficiency is realised by capturing a larger portion of the solar spectrum. The laboratory prototype of this new cell is reported to have an efficiency of 31% [8].

Some interesting research is under way to attempt to make solar cells from plastic materials rather than from crystalline silicon. This is, in effect, an attempt

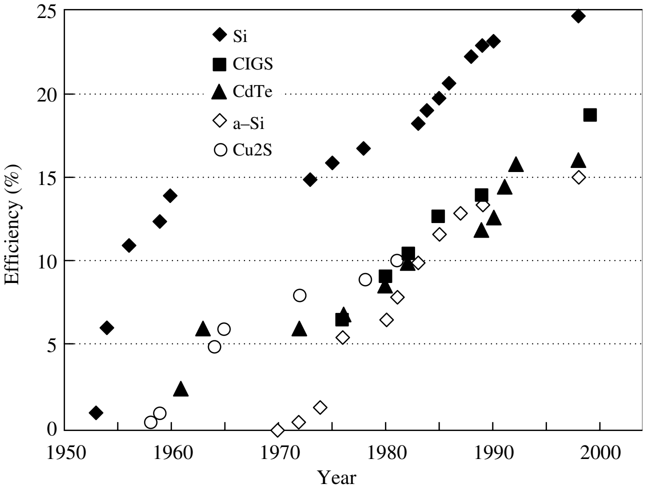


Fig. 12.4. Development of thin-film, photovoltaic cell efficiencies [7].
◆ crystalline silicon
■ copper indium gallium sulphide (CIGS)
▲ cadmium tellurium
◇ amorphous silicon
○ copper sulphide

to produce artificial photosynthesis using polymer (organic) materials to provide a self-assembling, two-phase, photovoltaic material [9].

The most remarkable form of photovoltaic conversion occurs in nature in the operation of photosynthesis in plants, described in the following chapter. Green leaves convert and store solar energy at a phenomenal rate in a chemical process that separates the functions of light absorption and charge transportation — a process that has been going on naturally for millions of years.

12.5. Operation of the Semiconductor Diode and Solar Photovoltaic Cell

Let a crystal of *p*-type material be brought into conjunction with a crystal of *n*-type material such that the junction represents perfect continuation of the lattice. Even in the unexcited state all of the charged sub-atomic particles are in constant motion due to thermal energy. Any increase of temperature causes the release of further electrons and holes due to the breaking of covalent bonds.

The most common form of *p–n* junction device is the semiconductor diode rectifier, which is probably the most frequently used component in electronic circuits. The application of an externally applied reverse voltage across a *p–n* junction device causes a small reverse leakage or thermal current. This condition is known as reverse bias or reverse blocking in electronic circuits. If a forward bias voltage is applied across a *p–n* junction device, the low resistivity of the semiconductor material results in the possibility of high forward current, which depends upon the external circuit impedance. The diode rectifier therefore has the nature of a terminal voltage-actuated, on–off switch.

A semiconductor *p–n* device can also be switched on by irradiating the *p–n* junction with photons of sufficient energy, and this is the basis of the solar photovoltaic cell. In a solar photovoltaic cell the incident solar radiation passes through the *p*-type material into the junction. Some photons of the incident radiation collide with the valence electrons of the silicon (for example) and are absorbed, releasing electrons and holes into the crystal lattice. If the silicon cell is electrically isolated on open circuit a direct emf or voltage will then appear across its terminals. If the cell has an external electrical circuit connected to its terminals, then a direct electric current (DC) will flow.

A *p–n* junction photovoltaic cell therefore performs two functions simultaneously: it harvests sunlight by converting photons to electric charges and it also conducts the charge carriers to the device terminals to become direct voltages. If a load is connected the charges go into motion and can be collected, as DC electric current.

12.6. Physical Properties of the Solar Photovoltaic Cell

The energy content W of the incoming radiation is in discrete packets that depend on its frequency, according to the relation

$$W = hf \tag{12.1}$$

where f is the frequency in Hz or s^{-1} and h is the Planck constant (6.626×10^{-34} Js or 4.136×10^{-15} eVs).

The frequency f of the radiation is related to its wavelength λ by the relation

$$f\lambda = c \tag{12.2}$$

where c is the velocity of light ($c = 2.998 \times 10^{8}$ m/s).

Combining (12.1) and (12.2) expresses the radiation energy in terms of wavelength.

$$W = \frac{hc}{\lambda} = \frac{1.986 \times 10^{-25}}{\lambda} \tag{12.3}$$

where the energy W is in joules when the wavelength λ is in metres. Alternatively, if the Planck constant is expressed in electron volt seconds (eVs),

$$W = \frac{hc}{\lambda} = \frac{1.24 \times 10^{-6}}{\lambda} \tag{12.4}$$

where now the energy W is in electron volts when the wavelength λ is in metres. The energy per photon at various parts of the solar spectrum, Fig. 11.1 of Chapter 11, is given in Table 12.1.

It is significant to note that only part of the incident solar radiation can produce a photovoltaic effect. The minimum amount of input energy per photon needed to liberate electrons into a lattice of crystalline silicon (sometimes called the "energy gap") is found to be almost 1.08 eV or 1.73×10^{-19} J. From (12.3) or (12.4) this occurs at a wavelength $\lambda = 1.15$ μm. The infrared portion of the solar spectrum, with $\lambda > 1.15$ μm, is useful for heating purposes but will not photovoltaically energise silicon [10].

Table 12.1. Photon energy, frequency, and wavelength for solar radiation.

		Energy per photon	
Wavelength (μm)	Frequency (Hz or s^{-1})	joules	electron volts
0.3 (ultraviolet)	9.99×10^{14}	6.62×10^{-19}	4.133
0.5 (visible light)	5.996×10^{14}	3.972×10^{-19}	2.48
1.0 (near infrared)	2.998×10^{14}	1.986×10^{-19}	1.24
1.15 (near infrared)	2.607×10^{14}	1.727×10^{-19}	1.0783
2.0 (infrared)	1.499×10^{14}	0.993×10^{-19}	0.62
3.0 (infrared)	0.9993×10^{14}	0.662×10^{-19}	0.413

When the wavelength is less than 1150 nm (1.15 μm) its energy content is greater than the critical energy va1ue of 1.08 eV. Electrons are released but the excess energy above 1.08 eV is absorbed by the silicon and re-appears as heat without contributing to the electric current flow. In the wavelength range $0.3 \leq \lambda \leq 1.15$ μm, at any particular frequency, a proportion $1.08/W'$ of the associated energy W' is wasted as heat. Over this spectral range a proportion 33% of the input energy is lost. This reduces the maximum theoretical conversion efficiency to 44% for a perfectly constructed crystalline silicon cell.

In addition to the intrinsic physical limitations above, any photovoltaic cell is subjected to further losses due to its electrical operation. The passage of current through the semiconductor material causes heating (I^2R) losses and this may be exacerbated by the contact resistance between the terminals and the cell active material. There is also power loss at the cell junction which must be strictly controlled to avoid overheating. These various forms of loss contribute additional components to the limitation of working efficiency. The final result is that an operational photovoltaic cell constructed of crystalline silicon has a maximum theoretical working efficiency of about 23%, although this is seldom attained or approached in commercial practice [11]. Recent (2000) laboratory prototypes claim efficiencies approaching 25% [7].

Maximum realisable efficiencies for various materials are shown in Fig. 12.5, which is a smoothed, approximate characteristic [12]. Each material has its own characteristically critical value of energy gap, corresponding to the 1.08 eV for silicon. As the junction temperature of a semiconductor material increases, its realisable efficiency is reduced. At 100°C, for example, the characteristic of Fig. 12.5 would be lowered, roughly uniformly, by about 40% and the maximum efficiency for silicon would drop to 14%. It can be seen that the materials gallium arsenide (GaAs), cadmium tellurium (CdTe) and aluminium antimony (AlSb), for example,

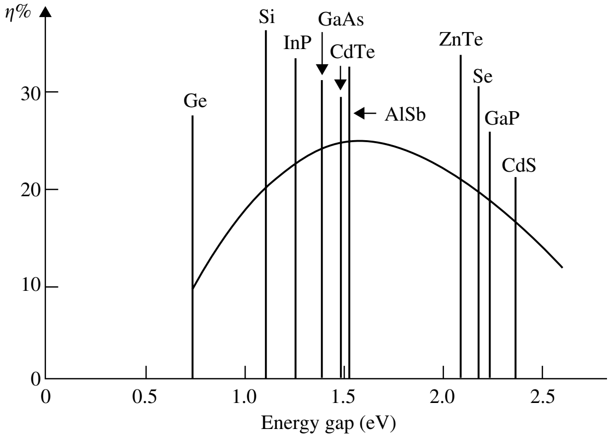


Fig. 12.5. Maximum realisable solar cell efficiencies for various materials at 0°C [12].

have potentially higher achievable efficiencies than silicon, but at present these are more expensive.

12.7. Electrical Output Properties of the Solar Photovoltaic Cell

The external characteristic of a solar cell is the property of current versus voltage. An ideal characteristic would be rectangular in shape. Practical characteristics are roughly rectangular, Fig. 12.6. Each different level of incident radiation results in a different characteristic. The intercept of a characteristic on the current axis represents zero voltage drop across the cell terminals and is the short circuit current I_{SC} which is (almost) directly proportional to the incident light intensity. This is true for individual silicon cells, Fig. 12.7, and also for solar arrays of many identical cells, Fig. 12.8 [12]. The intercept of an I–V characteristic on the voltage axis in Fig. 12.6 and Fig. 12.7 is the open circuit voltage V_{OC}, which varies logarithmically with the incident light intensity, Fig. 12.8. Most solar cells operate with a working level of direct voltage of less than 1 volt.

12.7.1. *Maximum power delivery*

In direct current circuits with a solar cell source the power generated is the product of the cell voltage and current. For typical characteristics like Fig. 12.6 the maximum power delivery point lies in the region of the knee of the curve. The current and voltage at the maximum power point P_m are defined here as I_{mp} and V_{mp} respectively, and the maximum power deliverable, for that particular value of insolation, is

$$P_m = I_{mp} V_{mp} \tag{12.5}$$

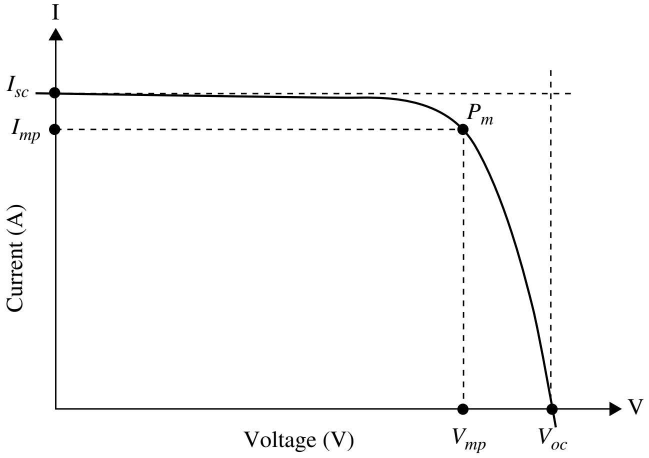


Fig. 12.6. External characteristic (current versus voltage) for typical photovoltaic cell.

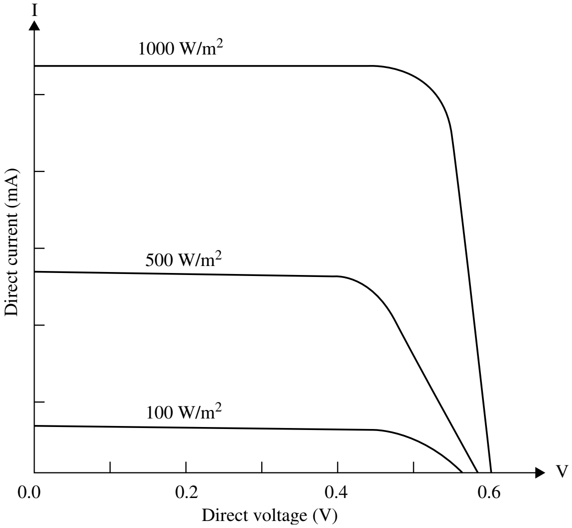


Fig. 12.7. Typical current–voltage characteristics of a solar photovoltaic cell [11].

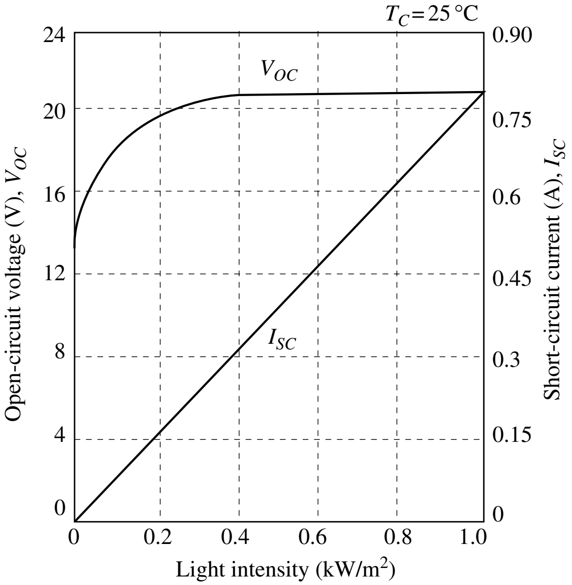


Fig. 12.8. Variation of V_{oc} and I_{sc} with solar insolation for a 36-cell solar module [12].

The cells manufactured by different companies have slightly different I–V shaped characteristics but they all follow the same pattern.

Most solar cell loads are resistive in nature. A load resistor R_L can be represented in the I–V plane by a straight line through the origin. Load resistance R_L

can vary from zero for short circuit operation to infinity for open circuit operation. In order to deliver the maximum possible power, for a specified level of insolation, R_L must satisfy the relationship

$$R_L = R_{mp} = \frac{V_{mp}}{I_{mp}} \tag{12.6}$$

12.7.2. *Equivalent circuits*

The electrical performance of a photovoltaic cell can be approximately represented by the equivalent circuits of Fig. 12.9, for the constant current regions of Figs. 12.6 and 7. A constant current generator which delivers its short circuit current I_{SC} is the power source and this is shunted by a nonlinear (i.e. does not obey Ohm's law) resistor R_j representing the variable junction resistance. For most circuit calculations the equivalent circuit of Fig. 12.9(b) is satisfactory. A more sophisticated, but more appropriate, representation is given in Fig. 12.9(a), where the internal series resistor R_S is much smaller than R_L, while the internal shunt resistor R_{sh} is much larger than R_L, for maximum power delivery.

The equations of circuit operation for Fig. 12.9(b) are

$$I = \frac{V}{R_L} \tag{12.7}$$

$$I_j = \frac{V}{R_j} \tag{12.8}$$

$$I_j = I_{SC} - I \tag{12.9}$$

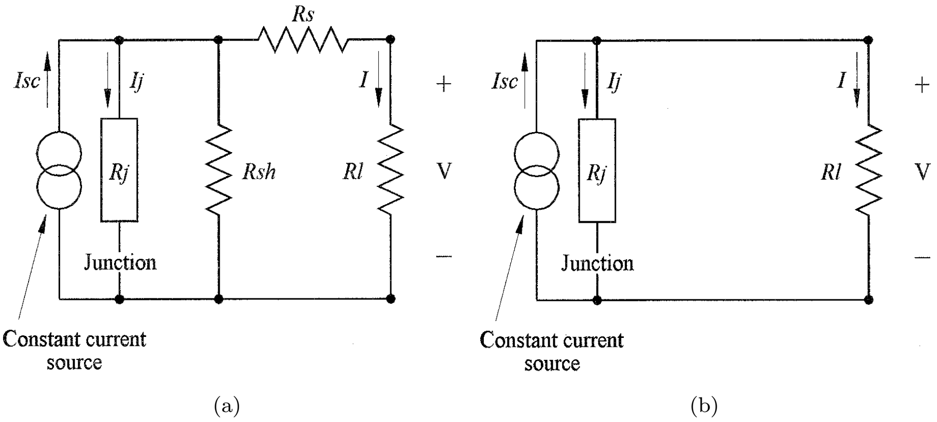


Fig. 12.9. Equivalent circuits of an irradiated solar cell [12].
I_{SC} = short circuit current I = load current
R_j = junction resistance R_L = load resistance
V = load voltage

$$R_j = \frac{V}{I_j} = \frac{V}{I_{SC} - \dfrac{V}{R_L}}$$

$$\therefore R_j = \frac{VR_L}{I_{SC}R_L - V} = \frac{IR_L}{I_{SC} - I} \tag{12.10}$$

Both forms of (12.10) for R_j depend on the accurate reading of the current–voltage characteristic. Also, the calculation of R_j involves taking the small difference between two relatively large values in the denominator term. This leads to inaccuracy so that R_j should be considered an approximate value.

The output power P_0 of a solar cell is given by the product of two DC values

$$P_0 = VI = \frac{V^2}{R_L} = I^2 R_L \tag{12.11}$$

12.7.3. *Load lines in the current–voltage plane*

A more detailed set of performance characteristics, for a typical cell, is given in Fig. 12.10. The slope of a load resistance line is defined by Ohm's law, (12.7). With a load resistance of 10 ohms, for example, the load line passes through the co-ordinates 0.1 V and 10 mA, 0.2 V and 20 mA, etc. while the 100 ohm load line passes through 0.1 V and 1 mA, 0.2 V and 2 mA, 0.3 V and 3 mA, etc.

If the load on a cell was, for example, a small electric motor, its load impedance characteristic would not be linear but roughly parabolic. In such a case an equivalent circuit would not be appropriate and analysis of the equations (12.7)–(12.11) would not apply.

The current–voltage characteristics of a solar cell cannot be expressed in analytical form but only by a general expression

$$I = f(V) \tag{12.12}$$

Any particular graphical characteristic could be approximated by a power series of many terms, but this would need to be obtained by a computer-based curve-fitting process. Usually there is no need for this level of calculation.

There is no way of calculating a maximum power point mathematically unless an analytic expression for the current–voltage characteristic is known. A maximum power point can, however, be calculated by iteration — making an initial guess as to the location and then taking successive co-ordinates and calculating the current–voltage product until a maximum value is reached.

Maximum power points for different levels of radiation usually occur at about the same voltage level and are therefore roughly proportional to the current. With the International Standard insolation of 1000 W/m^2, for example, the maximum power is delivered at 0.43 V and 48 mA in Fig. 12.10, which gives $0.43 \times 48/1000$ or 20.64 mW.

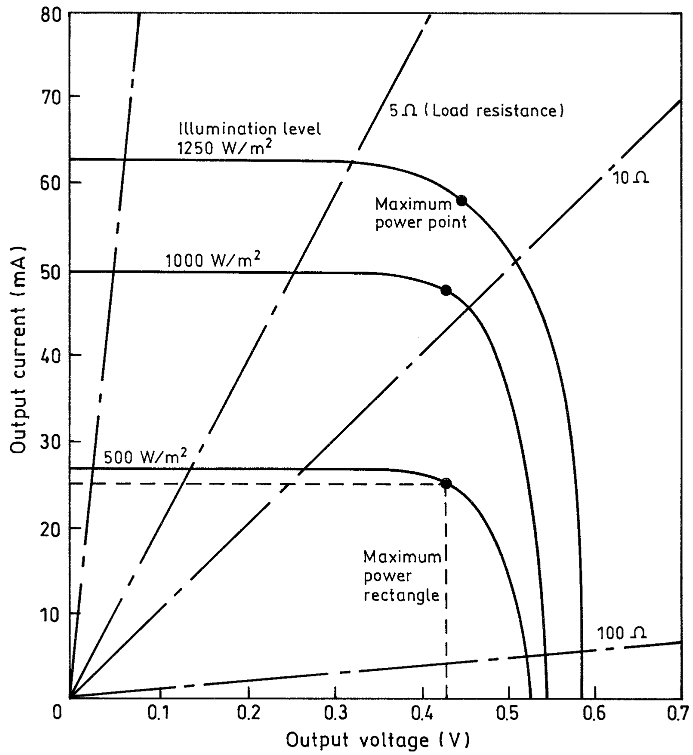
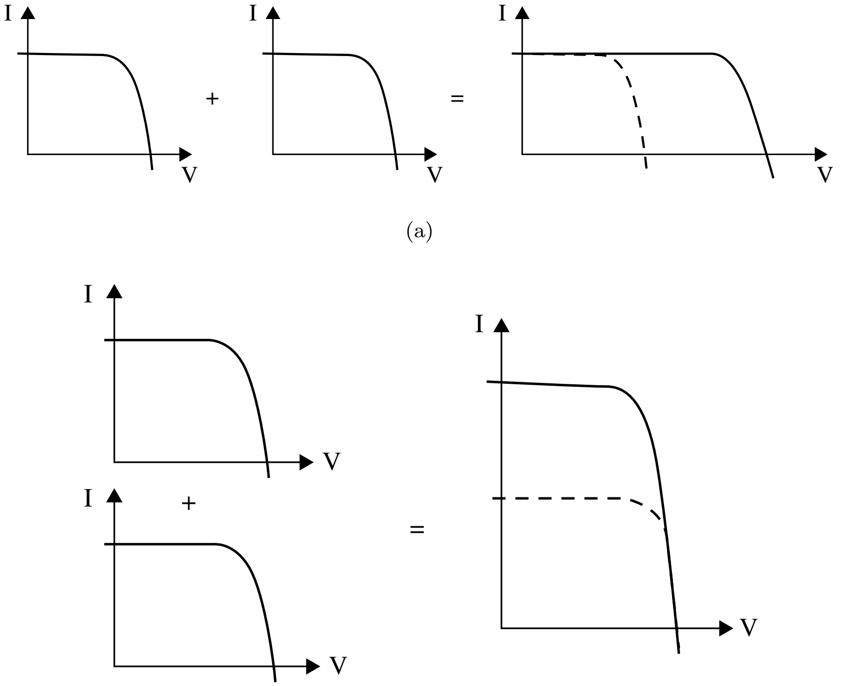


Fig. 12.10. Cell and load characteristic for typical cell (adapted from Ref. 13).

12.7.4. *Arrays of solar photovoltaic cells*

In order to deliver increased current to a load the appropriate number of solar cells has to be connected in parallel, whereas to deliver increased voltage the cells must be connected in series. Some load voltage and current specifications require values such that a series-parallel combination is needed. Clusters of cells are often referred to as solar arrays. The electrical output characteristics of simple series or parallel combinations of two identical cells are shown diagrammatically in Fig. 12.11 [14]. A common load application is for the full charging of a 12 V battery, which requires a level of 14–15 V from the battery charger. At a radiation of 1000 W/m^2 (Fig. 12.10), it would be necessary to use 15/0.54 or 28 cells in series of that particular manufacture. There would probably need to be several parallel-connected modules, each consisting of 28 cells in series, to supply the specified charging current.

An application requiring the direct connection of the array to provide a DC power supply of 120 V would require, effectively, 120/0.54 or 222 cells in series. Systems producing 600 V DC and hundreds of amperes of current are in operation worldwide.



(a)

(b)

Fig. 12.11. Output characteristics of solar cell arrays: (a) series combination, (b) parallel combination [14].

12.7.5. *Effect of temperature on solar cell operation*

When a solar cell is working, delivering current to a load, its temperature rises above the ambient. Temperature rises of 25–30°C are typical and this rise varies directly with the solar insolation. A rise of about 25°C can be expected at 900 $\mathrm{W/m^2}$.

$$\text{Cell temperature} = \begin{matrix}\text{Ambient}\\ \text{temperature}\end{matrix} + \begin{matrix}\text{Temperature}\\ \text{rise}\end{matrix} \tag{12.13}$$

In a high ambient temperature of (say) 25°C the cell working temperature could become $25 + 25 = 50$°C. With a low ambient temperature of (say) 5°C the temperature rise is the same, at the same insolation level, so that the cell working temperature will then be $5 + 25 = 30$°C.

A common effect of temperature rise is to slightly increase the short circuit current but more significantly to decrease the open circuit voltage. Overall, the effect is to reduce the maximum power available for a fixed value of radiation. Temperature effects are calibrated against an internationally agreed standard temperature of 25°C. These vary slightly for different designs of silicon photovoltaic cell. Data for several different cells are in the following ranges (with respect to 25°C) [14].

Effect of cell temperature on the short circuit current : $+(0.004 \text{ to } 0.013)\ \text{mA/cm}^2/^\circ\text{C}$

Effect of cell temperature on the open circuit voltage (voltage reduction coefficient) : $-(0.0023 \text{ to } 0.0028)\ \text{V/cell}/^\circ\text{C}$

Effect of cell temperature on the maximum power : $-(0.3 \text{ to } 0.5)\%/^\circ\text{C}$

The negative signs for V_{oc} and P_m above imply a reduction of value if the temperature rises above 25°C. Of course, the cell working temperature cannot naturally fall below the ambient level. The reduction of voltage of a module of series-connected cells can therefore be calculated from the relationship

$$\begin{matrix}\text{Voltage } (V_{oc}) \\ \text{reduction}\end{matrix} = \begin{matrix}\text{Number of cells} \\ \text{in series}\end{matrix} \times \text{Temp rise} \times \begin{matrix}\text{Voltage} \\ \text{reduction} \\ \text{coefficient}\end{matrix} \tag{12.14}$$

The overall temperature effect on the operating characteristic of a 36-cell solar array is given in Fig. 12.12 [12]. Increase of temperature has a greater effect on the voltage reduction than on current increase.

In locations where the ambient temperature is high the working temperature of a cell can become so large as to seriously impair its performance. It may then be necessary to employ some form of forced cooling, as shown diagrammatically in Fig. 12.13. It should be noted, from (12.13), that forced reduction of the ambient temperature, below the standard value of 25°C, causes a reduction of the cell working temperature. But the reduction of working voltage due to cell temperature rise still satisfies (12.14).

12.8. Applications of Photovoltaic Cells

The only mass use of the silicon photovoltaic cell is as the exposure meter or "electric eye" in cameras. In this application the low efficiency of 3–4% caused by the use of low-grade silicon is not significant.

Low power applications that incorporate photovoltaic cells include portable apparatus for remote locations. An array with an area of about 1 m^2 will provide several tens of watts of power, which is suitable for lighting purposes or for portable radio transmitter/receiver systems. With about 2 m^2 of cells sufficient power is available to drive a small water pump for irrigation purposes.

In a number of locations in the world solar cell arrays are used to power street lighting. During daylight hours the solar-generated energy is stored in a battery.

After dark, the battery is electronically connected to power the lighting and then automatically switched off again soon after dawn.

Large arrays have been used in certain commercial applications. For example, Fig. 12.14 shows a 100 kW system at Beverley High School, Beverley, Massachusetts, USA, that uses 3200 modules, each containing 36 solar cells. The system provides about 10% of the electricity demand [15]. There appears to be no electrical limitation of array size. Limitations may be posed by difficulties of fabrication, space available and the weight of the structure.

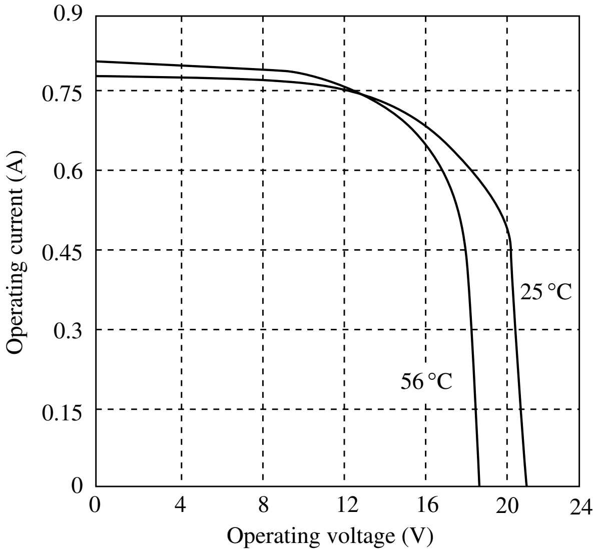


Fig. 12.12. Effect of temperature change on the operating characteristic for a 36-cell solar module [12].

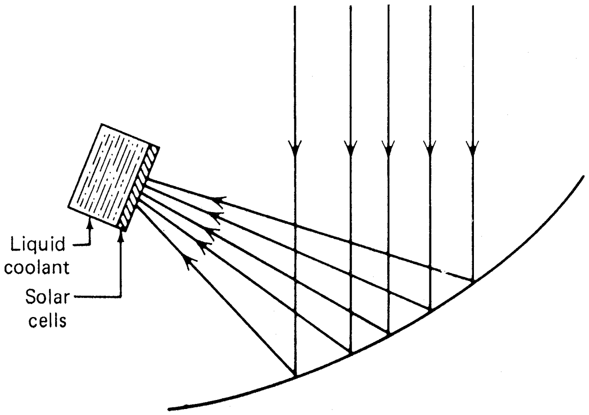


Fig. 12.13. Forced cooling of photovoltaic cells.

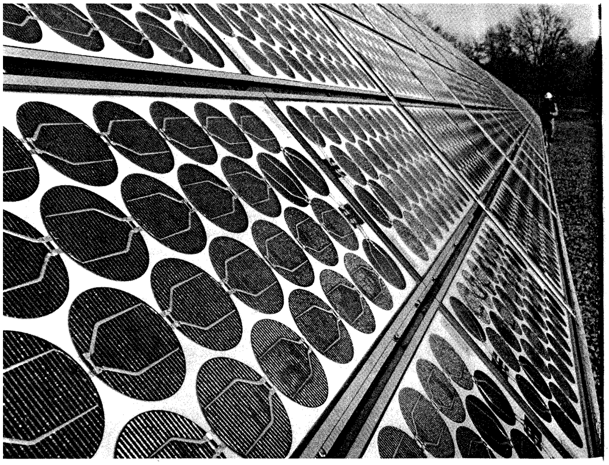


Fig. 12.14. 100 kW photovoltaic array [15].

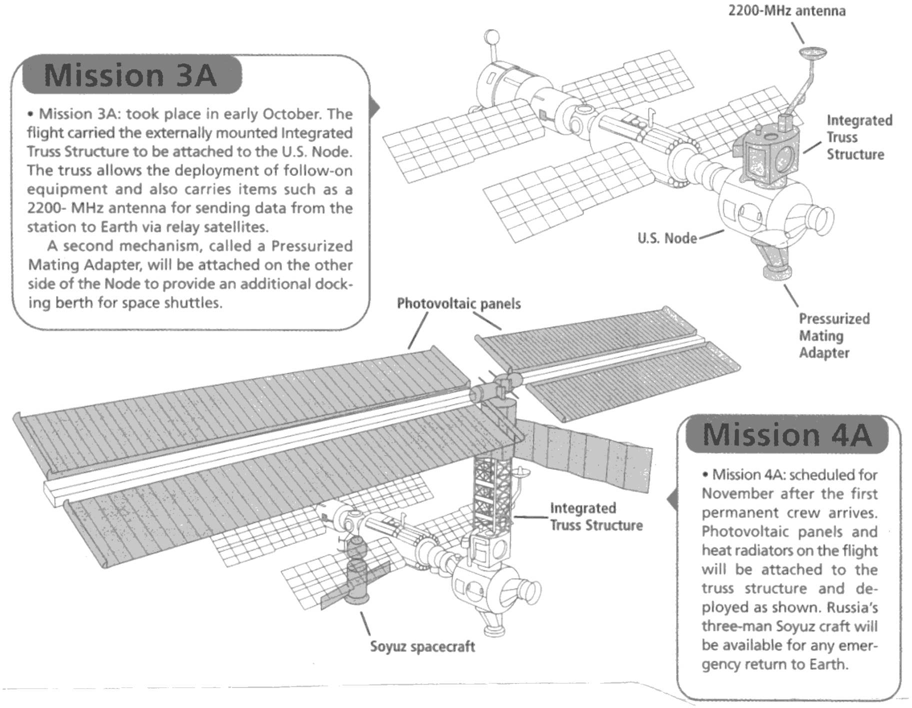
Large-scale use of solar photocells is also made in weather and telecommunication satellites and in space vehicles. The cells are constructed in sails, many metres square, which are folded away during launching and are unfurled by radio control after the satellite is in stable orbit. In space the cell assembly and support structure is weightless and can be directed towards the sun almost continuously, without intervening clouds. The failure of one of the solar arrays on the Hubble orbiting telescope was one of the problems that had to be solved by the US National Aeronautics and Space Administration (NASA) in the 1993 rescue mission.

The vast scale of modern space stations is illustrated in Fig. 12.15. Each of the four large solar photovoltaic panels has dimensions 240 ft × 38 ft, weighs 17.5 tons (earth weight) and is rated at 60 kW. The station orbits 5 miles/s at a height of 235 miles and has an expected lifetime of 15 years [16].

An intriguing possibility is the idea of power stations in space. A satellite in synchronous (i.e. geostationary) orbit could focus a beam of microwave power continuously onto a receiver antenna at a fixed location on earth, as illustrated by the artistic drawing of Fig. 12.16 [17].

Photovoltaic energy may be collected in space, using concentrator systems, and converted from DC power to microwave power. Energy storage is not a problem because a single satellite could view the sun for 23 out of every 24 hours and the solar flux is almost constant at its maximum ($m = 0$) value. To provide a power of 1000 $\mathrm{MW_e}$, the equivalent of a medium size power plant on earth, would require about 5 km^2 of cells, at an efficiency of 15%.

The basic scientific and engineering knowledge needed to mount such a massive project already exists. It would involve some major problems of satellite tracking and very precise guidance of the microwave beam. Waste heat from the microwave converters and generators would need to be radiated into space. The intensity of



Mission 3A

- Mission 3A: took place in early October. The flight carried the externally mounted Integrated Truss Structure to be attached to the U.S. Node. The truss allows the deployment of follow-on equipment and also carries items such as a 2200- MHz antenna for sending data from the station to Earth via relay satellites.

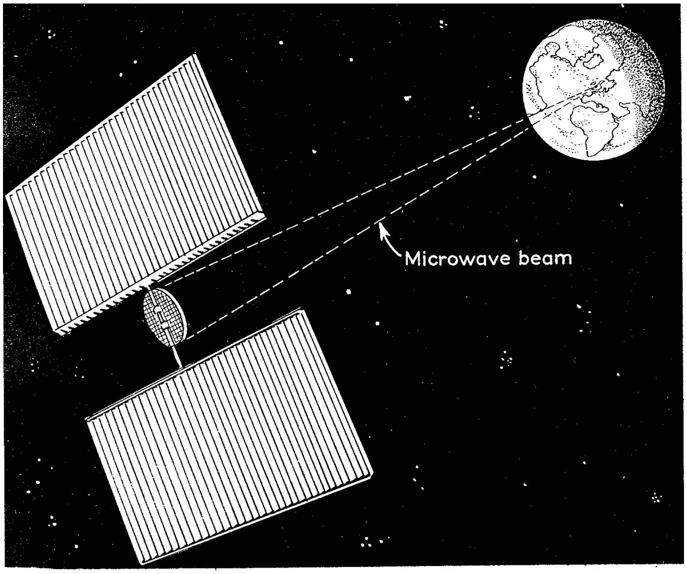
A second mechanism, called a Pressurized Mating Adapter, will be attached on the other side of the Node to provide an additional docking berth for space shuttles.

Mission 4A

- Mission 4A: scheduled for November after the first permanent crew arrives. Photovoltaic panels and heat radiators on the flight will be attached to the truss structure and deployed as shown. Russia's three-man Soyuz craft will be available for any emergency return to Earth.

2200-MHz antenna
Integrated Truss Structure
U.S. Node
Pressurized Mating Adapter
Photovoltaic panels
Integrated Truss Structure
Soyuz spacecraft

Fig. 12.15. International Space Station [16].



Microwave beam

Fig. 12.16. Electricity power plant in space [17]. (Artistic impression by P. E. Glaser of Arthur D. Little, Inc.)

radiation of the microwave beam could have destructive effects on plant and animal life if it was misdirected — rather like the "death ray" that features in some films and novels. Building and maintaining a project of this size would involve continuous manning by operational personnel and frequent trips for the space shuttle. It therefore raises the questions of human life and health in space. The massive cost could only be borne by governmental funding, or with governmental participation.

Solar photovoltaic electricity power stations on earth are an existing reality. They comprise a solar cell array — usually combined with some form of concentrator system, a storage battery facility capable of accepting most or all of the solar power output and a suitable control system. Terrestrial or earth-bound solar power stations are only viable in regions of intense radiation, such as North Africa, the Middle East, and countries with a Mediterranean climate, like the southern parts of the USA, and Mexico.

The Winston compound parabolic concentrator, described in Sec. 11.5.2 of Chapter 11, can also be used for solar photovoltaic energy capture. Because the efficiency of conversion is reduced at high temperatures it is usually necessary to use liquid cooling for silicon cells, as illustrated conceptually in Fig. 12.13.

A commonly used form of concentrator in photovoltaic systems is the Fresnel lens optical system. This is a refracting lens system that uses glass or plastic lens material in which concentric (or parallel) grooves are cut or moulded. The grooves are shaped and arranged to make all the light converge to a point or along a line, Fig. 12.17. Common uses of Fresnel lens systems include theatrical spotlights. Lighthouse rotating warning lights invariably use large Fresnel lens systems. Lower power applications include solar cookers and solar furnaces. The Fresnel lens concentrates the input radiation like a magnifying glass. Use of Fresnel lens systems can provide the equivalent of 50 times the normal solar radiation, sometimes referred to as "50 suns". [Note that this is not the same as a concentration ratio of 50, as defined in (11.6) of Chapter 11, which refers to a ratio of two areas.]

A 350 kW solar voltaic system is in operation supplying two villages outside Riyadh, the capital city of Saudi Arabia. An assembly of 160 photovoltaic arrays, Fig. 12.18, using Fresnel lens concentrators, delivers power to the 1100 kWh lead-acid storage batteries and also provides input power to the local 60 Hz electricity grid through a DC-to-AC three-phase inverter. One of the local environmental features is desert sandstorms and the Fresnel lens surfaces are cleaned manually by washing with water [18].

Most of the serious research work on solar photovoltaic electric power generation is now taking place in Germany, Japan and the USA. Various installations with ratings of the order of a few hundred kW, up to a few tens of MW, are planned or under development or are now in commission. This includes a design for a community college in Arkansas, USA, with an electrical output of 320 kW from 59,400 single-crystal silicon cells incorporating parabolic trough tracking concentrator collectors with an average concentration of 30 suns.

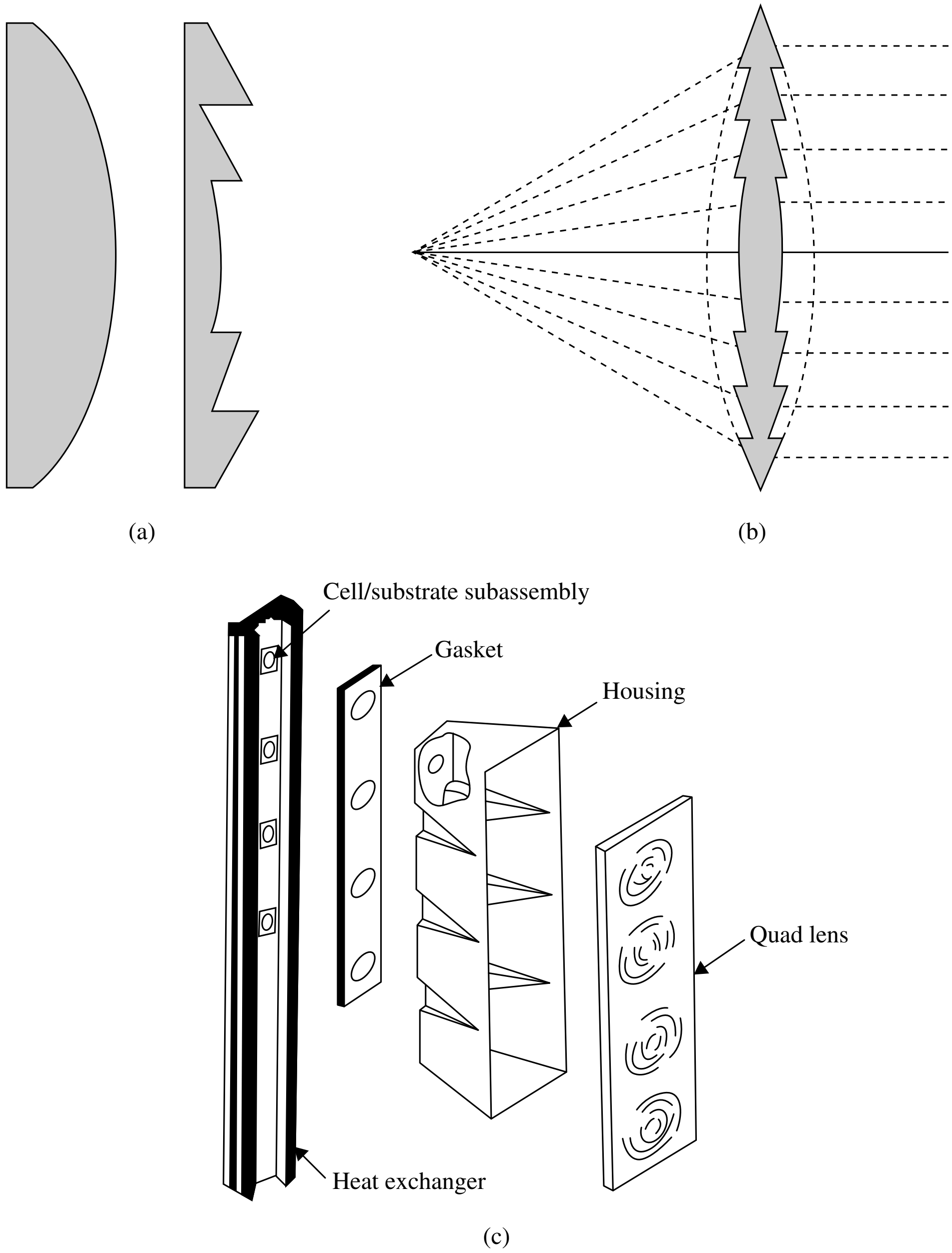

(a)
(b)
Cell/substrate subassembly
Gasket
Housing
Quad lens
Heat exchanger
(c)

Fig. 12.17. Fresnel lens
*(a) basic structure of three-ring lens
**(b) light distribution in double-sided, four-ring lens
(c) assembly structure of four-cell array
*http://www.talura.dk/optics/fresnel.html
**http://hyperphysics.phy-astn.gsu.edu/hbare/geoopt/fresnellens.html

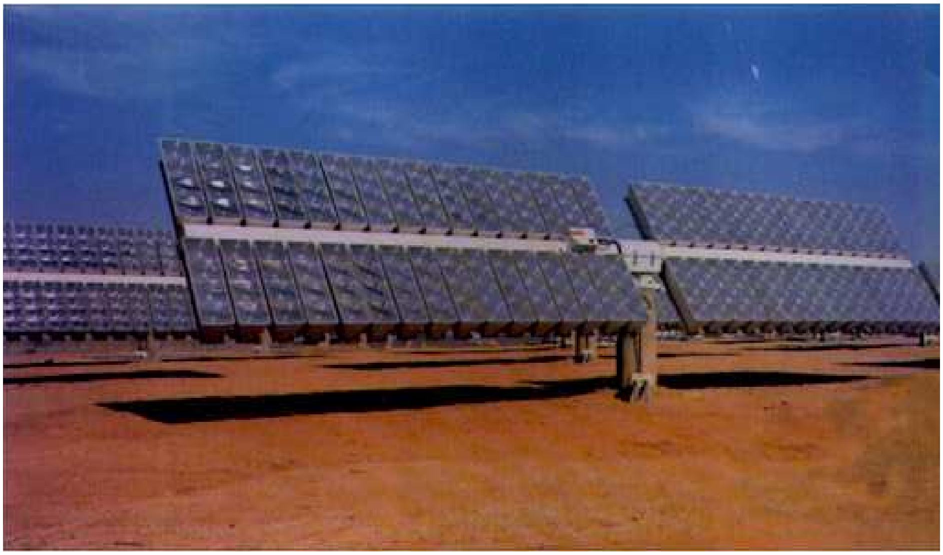


Fig. 12.18. Concentrator photovoltaic array in Saudi Arabia [18] using four-cell units.

In Arizona, USA, an experimental 20 kW photovoltaic array has been built using innovative cells made of crystalline silicon. These are mounted under acrylic concentrating lenses and are reported to have conversion efficiencies greater than 20%. A 100 MW photovoltaic array using thin-film silicon technology is proposed for the US Department of Energy's site at Nevada [19]. Annual US shipments of photovoltaic cells increased from almost zero in the early 1970s to greater than 75 MW in 1996 and to 77 peak MW in 1999. Crystalline silicon cells continue to dominate the US market, accounting for 96% of the total shipments in 1999 [20]. In the USA the industrial sector has now (2002) replaced the residential sector as the largest market for PV cells and modules.

12.9. The Future Challenge for Photovoltaics

The challenge in the development of photovoltaic materials is demonstrated in Fig. 12.19, which compares the spectral profile of the sun (at $m = 0$) with the corresponding profile for commercial grade silicon. In a radio or telecommunications system these two curves would be described as a bad mismatch. The sun profile is not going to change. What is needed is a cheap and abundant material with a spectral response that is a better fit to the solar characteristic and has a high energy conversion efficiency. Alternatively, the need could be satisfied with some type of radiation matching device (which is, in effect, a frequency changer) between the input solar radiation and the spectral profile of the solar cell material. Enormous

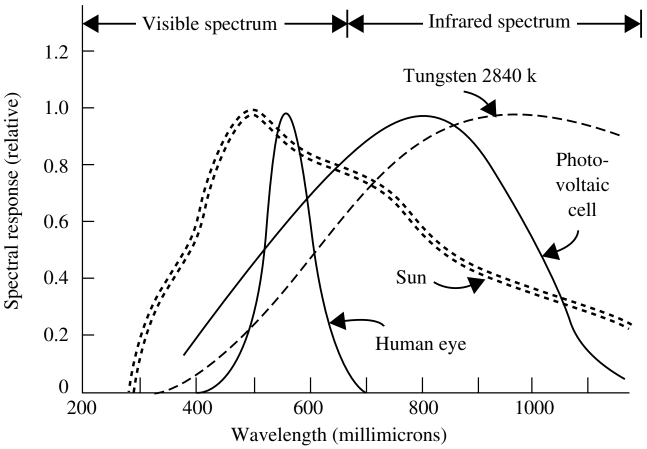


Fig. 12.19. Spectral responses of sunlight and a silicon photovoltaic cell (unknown origin).

research effort is presently devoted to this task all over the world. The highest scientific accolade and great wealth will go to the successful inventor/discoverer.

Most of the work now under way involves government-sponsored or government-subsidised research prototypes. The big commercial future for photovoltaic electric power generation still awaits the development of a much cheaper photocell.

12.10. Worked Examples

Example 12.1

A solar cell array has a current–voltage characteristic, at the standard insolation of 1000 W/m^2, in which $V_{oc} = 11.5$ V and $I_{sc} = 1.75$ A. For a particular resistive load $V_{mp} = 7.75$ V and $I_{mp} = 1.15$ A. Calculate the maximum power deliverable and the load resistance that will result in maximum power delivery

From (12.5)

$$P_m = V_{mp} I_{mp} = 7.75 \times 1.5 = 11.625\ W$$

From (12.6)

$$R_{mp} = \frac{V_{mp}}{I_{mp}} = \frac{7.75}{1.5} = 5.17\ \Omega$$

Example 12.2

Two modules of solar cells were measured on different days with different weather conditions to give the following data:

	I_{sc} (A)	Insolation (W/m^2)
Module 1	1.25	400
Module 2	1.05	325

Which module has the larger I_{sc} measured at the standard insolation of 1000 A/m^2?

It can be assumed that I_{sc} is proportional to the insolation

$$\text{For module 1} \quad I_{sc} = \frac{1000}{400} \times 1.25 = 3.125 \text{ A}$$

$$\text{For module 2} \quad I_{sc} = \frac{1000}{400} \times 1.05 = 3.23 \text{ A}$$

The calculation shows that module 2 has the higher standard value of I_{sc}.

Example 12.3

A 28-cell module of a solar array has $V_{oc} = 17$ V at 25°C. What will be the value V_{oc} at 60°C if the cell data specifies 0.0024 V/°C/cell?

Temperature difference = 35°C
From (12.14) the reduction of open circuit voltage is given by:
Voltage reduction = $28 \times 35 \times 0.0024 = 2.35$ V
Working value of V_{oc} is $V_{oc} = 17 - 2.35 = 14.65$ V
This represents a reduction of 2.35/17 or 13.8%.
If the short circuit current is only slightly increased by the temperature rise, the implication here is that the maximum power will decrease by the order 10–12%.

Example 12.4

In the current–voltage characteristics of Fig. 12.10 for a typical photocell, what values of load resistance would result in maximum power output at the three specified radiation levels?

At 1250 W/m^2, maximum output power P_0 occurs when $V = 0.447$ V and $I = 58.1$ mA so that $P_0 = 0.447 \times 58.2/1000 = 25$ mW.

Similarly, at 1000 W/m^2, for maximum output power it is seen that $V = 0.428$ V and $I = 48$ mA, giving $P_0 = 20.54$ mW.

Also, at 500 W/m^2 input radiation, the maximum output power occurs at $V = 0.428$ V and $I = 25.2$ mA, so that $P_0 = 10.8$ mW.

It can be deduced from these results that the maximum output power is proportional to the input radiation power, within about 5% error.

The load resistances for the three cases are obtained from (12.6).

P_{in} (W/m^2)	P_0(max) (mW)	R_{load} (ohms)
1250	26	$447/58.2 = 7.68$
1000	20.54	$428/48 = 8.92$
500	10.8	$428/25.2 = 16.9$

Example 12.5

The typical photocell with characteristics depicted in Fig. 12.20 is delivering power to the load resistance $R_L = 7.5\ \Omega$ with an input radiation of 1000 W/m^2. What is the value of the junction resistor R_j in the equivalent circuit?

With $R_L = 7.5\ \Omega$ the resistance line intersects the 1000 W/m^2 characteristic at a point P, Fig. 12.15, where the terminal voltage $V = 0.364$ V.

If the simplified equivalent circuit of Fig. 12.9(b) is used, then the load current is

$$I = \frac{V}{R_L} = \frac{0.364}{7.5} = 0.0485 \text{ A} = 48.5 \text{ mA}$$

The constant current delivered by the constant current generator is the short circuit value of 50 mA. With 7.5 Ω load the junction resistor current is therefore, from (12.9),

$$I_j = I_s - I = 50 - 48.5 = 1.5 \text{ mA}$$

Junction resistor R_j therefore has the value

$$R_j = \frac{V}{I_j} = \frac{0.364}{\frac{1.5}{1000}} = \frac{364}{1.5} = 242.7\ \Omega$$

Example 12.6

A certain type of commercial solar photovoltaic cell has $V_{mp} = 0.48$ V and $I_{mp} = 20$ mA/cm^2 under standard insolation conditions. What combination of cells would be required to fully charge a nickel–cadmium battery requiring 4.2 V and 70 mA?

$$\begin{array}{c}\text{Number of cells in series}\\ \text{to supply the voltage}\end{array} = \frac{4.2}{0.48} = 8.7 \quad \text{(say 9)}$$

$$\begin{array}{c}\text{Area of solar cell}\\ \text{material to generate}\\ \text{the required current}\end{array} = \frac{70}{29} = 2.4 \text{ cm}^2$$

The number of parallel-connected cells to generate the required current will depend on the individual cell areas. A standard size of cell is 1 cm^2, which would require 2.4 cells in parallel. This is obviously not possible and the choice might be 3 cells of standard size.

With 3 cells of 1 cm^2 in parallel,

$$I_{mp} = 3 \times 29 = 87 \text{ mA}$$

One possible design choice is therefore to use 3 parallel branches, each containing 9 cells in series. A parallel-connected resistor across the load would divert the excess $87 - 79 = 8$ mA of current if required, although this would be a wasteful solution.

Example 12.7

A number of identical solar cells, having the characteristics of Fig. 12.20, are connected in parallel. How many cells would be needed to deliver 1 A of current to a 10 Ω load resistor with an input radiation level of 1000 W/m^2?

With a load resistance of 10 Ω the load line intersects the current–voltage characteristic for 1000 W/m^2 at the co-ordinate $V = 0.46$ V and $I = 45$ mA.

At 1000 W/m^2 the short circuit current is 50 mA. Each constant current generator is therefore delivering 5 mA of current to its identical junction resistor, and 45 mA to the load resistor, Fig. 12.21. To deliver 1 A, therefore,

$$\text{Necessary number of cells } n = \frac{1}{\frac{45}{1000}} = 22.22$$

The design choice is to use either 22 or 23 cells.
With 22 cells, $I = 22 \times 0.045 = 0.99$ A
With 23 cells, $I = 23 \times 0.045 = 1.035$ A

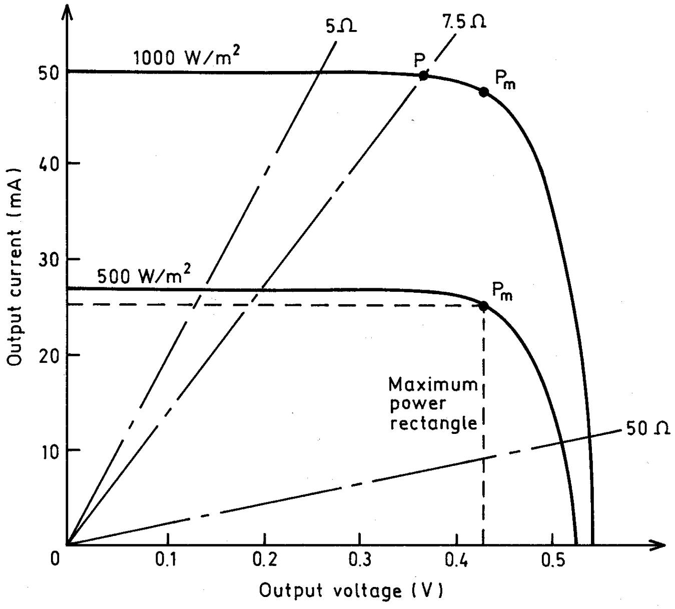


Fig. 12.20. Specimen photovoltaic cell characteristics.

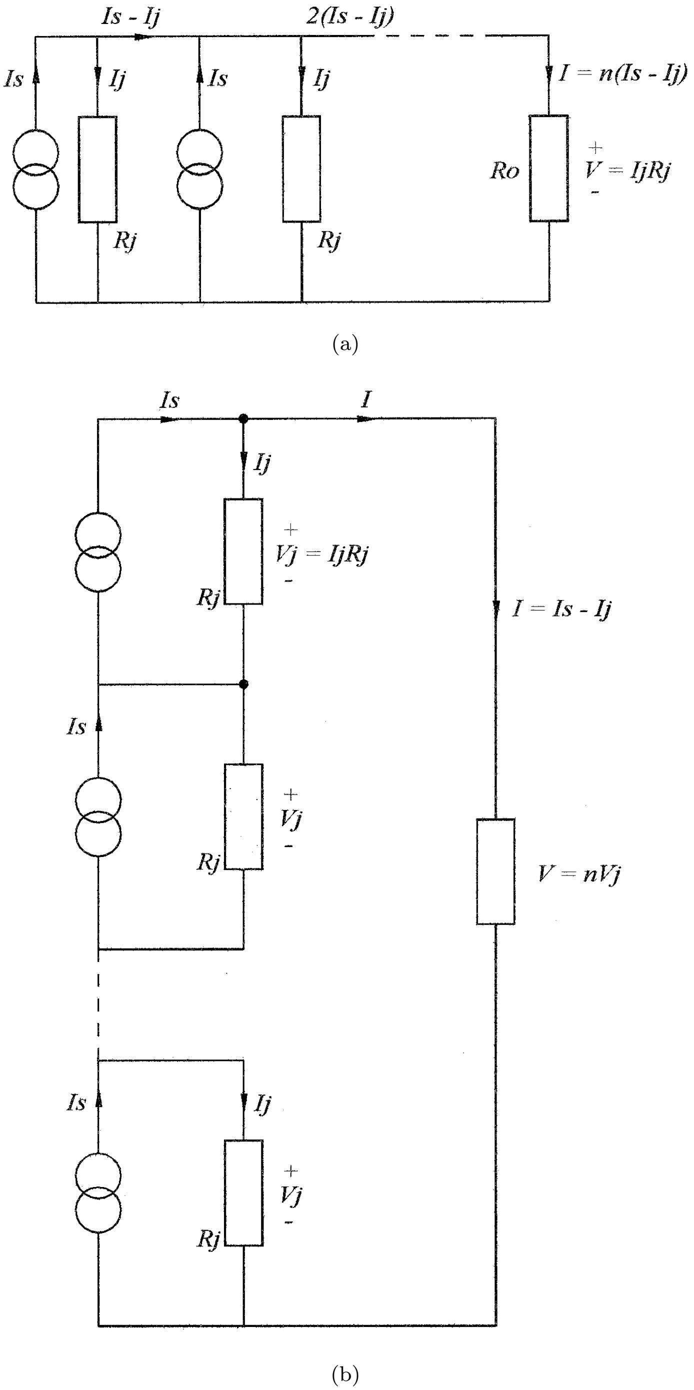

Is - Ij
2(Is - Ij)
Is
Ij
Is
Ij
I = n(Is - Ij)
Ro
+
V = IjRj
-
Rj
Rj
(a)
Is
I
Ij
+
Vj = IjRj
-
Rj
I = Is - Ij
Is
+
Vj
-
Rj
V = nVj
Is
Ij
+
Vj
-
Rj
(b)

Fig. 12.21. Equivalent circuits for the connection of identical solar cells: (a) parallel, (b) series.

Example 12.8

A number of identical solar cells, having the characteristics of Fig. 12.20, are connected in series. How many series connected cells are needed to deliver an output of 10 V to a 10 Ω load resistor with an insolation level of 1000 W/m^2.

With a load resistance of 10 Ω the load line intersects the 1000 W/m^2 current – voltage characteristic at the co-ordinate $V = 0.46$ V and $I = 45$ mA.

At 1000 W/m^2 the short circuit current is 50 mA. Each constant current generator therefore delivers 5 mA of current to its junction resistor R_j, and 45 mA to the load resistor, Fig. 12.21(b).

The load current is equal to the constant current-source value of 45 mA. The load voltage is the sum of n series-connected identical voltage drops V_j.

$$V = nV_j = n \times 0.46$$

To deliver a load value of 10 V requires

$$n = \frac{10}{0.46} = 21.74$$

The design choice is to connect either 21 or 22 cells in series
With 21 cells, $V = 21 \times 0.46 = 9.66$ V
With 22 cells, $V = 22 \times 0.46 = 10.12$ V

Example 12.9

In a particular location in the USA the solar insolation has a power density of 1000 W/m^2 for an average of 112 hours/month. The energy demand is for 1500 kWh/month. This can be provided by a solar cell array with an estimated lifetime of 20 years. The cost of the solar cells is about \$3 per peak watt. Fabrication, maintenance and interest on the capital cost effectively (at least) doubles the price per peak watt. Calculate the cost of the energy per kWh.

$$\text{Required power} = \frac{1500}{112} = 13.4 \text{ kW average}$$

$$\text{Cost} = 13{,}400 \times 3 \times 2 = \$80{,}400$$

$$\begin{aligned}
\text{Energy consumed in 20 years} &= 1500 \times 12 \times 20 \\
&= 360{,}000 \text{ kWh} \\
\text{Cost per kWh} &= 80{,}400/360{,}000 \\
&= \$0.223/\text{kWh}
\end{aligned}$$

This should be regarded as a minimum and rather optimistic figure. The present (2002) tariff for electricity in the USA is about \$0.07/kWh. The cost of solar-generated electricity therefore needs to be reduced by a factor of 3 (and probably more) in order to be competitive. The fabrication, maintenance and financing charges on an installation are not likely to undergo dramatic change. A major reduction (i.e. at least five-fold) in the cost of manufacturing the photovoltaic material, or improving its efficiency, or both is required.

12.11. Problems and Review Questions

Basic physics of solar photovoltaic cells

12.1. List the advantages of photovoltaic cells compared with solar thermionic applications.

12.2. Describe the atomic structure of silicon and explain the term "covalent bond".

12.3. Describe the differences between the types of silicon semiconductors known as (a) monocrystalline, (b) polycrystalline, (c) amorphous.

12.4. Explain the terms "n-type silicon" and "p-type silicon".

12.5. What is the minimum energy of the incoming radiation that will cause electrons to flow across the energy gap in silicon? How is this energy related to the frequency, wavelength and velocity of the radiation?

12.6. Why does the efficiency characteristic of Fig. 12.5 fall off at high values of the energy gap?

12.7. What is the effect of temperature on the efficiency of a photovoltaic cell operation?

Photovoltaic materials

12.8. What are the principal difficulties in manufacturing single-crystal silicon for use in photovoltaic cells?

12.9. What is the principal advantage of producing single-crystal silicon by growing the crystal in the form of a ribbon rather than a cylindrical ingot?

12.10. Gallium arsenide is capable of converting energy at higher theoretical working efficiencies than silicon in photovoltaic cells. What are the objections to its widespread use?

12.11. What is the main advantage of polycrystalline silicon solar cells compared with single-crystal cells?

12.12. Specify the reasons why solar cells have such low values of conversion efficiency.

12.13. Why are solar concentrators often used in photovoltaic cell applications?

12.14. What is the effect of increased temperature on the photo-conversion efficiency of a photovoltaic cell?

12.15. In space the area of photocells needed to produce a specified power output is only a fraction of the area that would be required at the earth's surface. Why is this?

Electrical output properties of photovoltaic cells

12.16. Sketch the current–voltage characteristic of a typical solar photovoltaic cell. Identify the points of operation for (i) open circuit voltage, (ii) short circuit current, (iii) maximum power delivery.

12.17. Sketch the current–voltage characteristic of a typical solar photovoltaic cell. Identify the point of operation for maximum power delivery. How would you determine this location?

12.18. For a silicon photovoltaic cell what are the approximate values of the ratios (i) V_{mp}/V_{oc}, (ii) I_{mp}/I_{sc}?

12.19. A module of solar cells has $I_{sc} = 1.5$ A when the radiation is 1000 W/m^2. What will be the value of I_{sc} when the radiation is (i) 850 W/m^2, (ii) 300 W/m^2?

12.20. For the solar cell characteristics of Fig. 12.10 identify the operating voltage and current values, with load resistances of 8 Ω and 20 Ω, for radiation levels of (i) 1000 W/m^2, (ii) 500 W/m^2.

12.21. The temperature effects on a certain solar cell are specified as -0.0024 V/°C/cell and $+0.006$ mA/°C/cm^2. A modular array of 30 cells generates $V_{oc} = 19$ V at 25°C. What is the change of V_{oc} for each 10°C rise of cell temperature? Estimate the percentage change in the value of maximum power P_m at the same insolation level.

12.22. Sketch an equivalent circuit for a silicon solar photovoltaic cell. How is the source current of your equivalent circuit related to the solar radiation falling on the cell?

12.23. For the solar cell characteristic representing 500 W/m^2 of Fig. 12.20, develop an equivalent circuit for operation at the maximum power point P_m. Calculate values for the load resistance, junction resistance and branch currents.

12.24. In a silicon solar cell the effective junction resistance R_j varies with current. For a constant insolation of 1000 W/m^2, using the characteristic in Fig. 12.20, calculate values of R_j with load resistances of 5 Ω, 10 Ω and 50 Ω. Sketch the form of variation of R_j with current over the whole operating range.

12.25. The solar cell that is characterised in Fig. 12.20 operates with a fixed load resistance of 5 Ω. How does the value of the junction resistance R_j vary as the radiation level falls from 1000 W/m^2 to 500 W/m^2?

12.26. For the solar cell characteristics of Fig. 12.10, what value of load resistor would result in a load line passing through the maximum power point P_m at 1250 W/m^2?

12.27. For the solar cell characteristics of Fig. 12.20, what value of load resistor would result in a load line passing through the maximum power point P_m at 1000 W/m^2?

Combinations of solar cells

12.28. An array of solar cells consists of two parallel branches, each of three cells connected in series. Sketch a simple diagram, of the form of Fig. 12.11, to illustrate the overall *I–V* characteristic.

12.29. A solar array consists of three parallel branches, each containing two identical cells in series. Sketch a diagram of the overall *I–V* characteristic, compared with the *I–V* characteristic of each individual cell.

12.30. Twenty solar cells of the type characterised in Fig. 12.20 are connected in parallel to a 10 ohm load. Calculate the load current, voltage and power when the radiation is (i) 1000 $\mathrm{W/m^2}$, (ii) 500 $\mathrm{W/m^2}$.

12.31. How would you realise a terminal voltage of 10 V using solar cells of the type characterised in Fig. 12.20?

12.32. At a radiation level of 1000 $\mathrm{W/m^2}$, with a load resistance of 10 Ω, 100 solar cells of the type characterised in Fig. 12.20 are connected in series. Calculate the current, voltage and power at the load terminals.

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CHAPTER 13

BIOLOGICAL ENERGY AND CHEMICAL ENERGY

13.1. Biomass and Biofuels

Any type of animal or plant material that can be converted into energy is called biomass. This includes trees and shrubs, crops and grasses, algae, aquatic plants, agricultural and forest residues plus all forms of human, animal and plant waste [1]. When the material is used for energy production it becomes a biofuel. There are many forms of biofuel, existing in solid, liquid or gaseous categories.

An estimate of the world solid biomass standing in forests in 1979 was 1.8×10^{22} J. At that time this figure was comparable with the world's proven natural gas and oil reserves [2]. The same biomass figure is about 50 times the value of world primary energy consumption in 2000, recorded in Table 2.3. If the biomass values of grasslands and crops are included (although these are mainly used for food production — indirectly energy — rather than fuel supply) the solid biomass figure is about 200 times the global energy consumption.

The main sources of raw material that constitute biofuels include

(a) Natural vegetation
(b) Energy tree plantations
(c) Specific energy crops
(d) Wastes
(e) Water-based biomass

Each of the above five categories is briefly discussed below.

13.1.1. *Natural vegetation*

In harvesting a natural vegetation site no energy costs are involved in clearing or replanting. Where an area may be unsuitable for agriculture the use of its vegetation for biomass would constitute a useful bonus biofuel source. There still remain the necessary costs of harvesting the vegetation and transporting it to a user site. A

Photo credit: USDA-Soil Conservation Service

Fig. 13.1. Commercial forestry [10].

disadvantage is that even in fertile locations the yields are low — about one-half of the value that might be obtained from customised energy plantations.

13.1.2. *Energy tree plantations*

Trees and other types of lignocellulose materials may be grown specifically for burning as biofuels. By the choice of appropriate species, sites, planting densities and harvesting schedules biofuels can be grown at competitive costs. This process is sometimes referred to as "short rotation forestry". An example of coniferous forestry in the USA is given in Fig. 13.1.

13.1.3. *Specific energy crops*

Certain crops have high energy conversion efficiency. In appropriate locations crops such as eucalyptus trees, rubber plants or sunflowers might be used because of their rapid growth and high energy content [3]. Such crops do not have to be consumable by humans or animals, and the entire crop can be used, including leaves, stalks and roots. The stored chemical energy can be converted directly to heat by combustion or processed into liquid or gaseous fuels. Liquid biofuels are discussed in detail in Sec. 13.3.4 below.

Energy farming, like other agricultural operations, requires large quantities of water. In the developed countries of the western world there is competition for the use of land, water and nutrients with various forms of food production, including animal farming. An interesting economic issue is whether crops in growth command higher prices as fuel rather than food or fibre. Crop surpluses would provide low-cost biomass, but is surplus food production the best overall use of the land and water?

There is a further potential disadvantage to the use of land-based energy farming. The hardy and fast-growing species required for energy use could become widespread nuisances if they escaped from the confines of the farm. They may then displace native plant species and impact on animal and insect life. Also, the methods necessarily used to control infestations and disease in the energy plants, especially if they are monocultures, could have adverse effects on neighbouring food production crops.

The same soil plantation may be used for two species of plants with out-of-phase growth patterns. If both species are in leaf together the leaf canopy cover profile is increased. Non-nitrogen-fixing crops can be grown side by side with legumes to reduce the need for nitrogenous fertilisers. Mixed cropping of this kind is less susceptible to damage by external parasites or predators than monoculture plantations [4].

There are some plants that produce high concentrations of "petroleum-like" products. These can be grown en masse and the "oils" extracted or squeezed out. Pilot schemes have been carried out in Mexico.

Widespread energy farming on marginal land implies the need for some level of overall control. A fast-growing plant that thrived in marginal conditions would create incentives to adapt the plant for food production. This is not necessarily bad but would create further pressure on land use for purely biomass reasons. In other words, the food versus biomass competition would increase.

It would seem sensible to think in terms of integrated growth mixed cropping, in which energy crops are developed alongside crops for food, fertilisers and chemicals [4].

13.1.4. *Use of wastes*

The burning and biodegradation of wastes as a source of energy is so significant an issue that a complete section below (Sec. 13.5) is devoted to this.

13.1.5. *Water-based biomass*

Aquatic plants do not require irrigation or appreciable rainfall. Water temperatures fluctuate less than land temperatures and light absorption is high, giving rise to high photosynthetic efficiencies.

Algae, seaweed and other aquatic lower plants can be intensively grown in certain areas of the sea or in inland lakes or ponds. This would eliminate the competition for land with conventional agriculture. On average, the oceans are low in plant nutrients. Surface waters have low natural productivity but sometimes act as nutrient repositories due to runoff from the land. Deep ocean waters are rich in nutrients. If such deep water can be pumped to the surface a biomass crop such as giant kelp (large brown seaweed) could be grown [1,3]. Yields of up to several hundred tons per acre per year are possible.

A typical alga farm might contain an acre of land, excavated to a depth of 18 inches, flooded, and alga plants introduced. The pond would be covered with plastic, injected with carbon dioxide and maintained at a temperature of 100°F using (say) power station cooling water, which is presently dumped into rivers. As the algae is harvested the nutrient-rich water used for growth is returned to the pond and re-seeded to recycle the operation [5].

The aquatic weed known as water hyacinth has been studied as a tropical water source of biogases, particularly by the US National Aeronautics and Space Administration (NASA) [6]. On a dry weight base, 1 kg of water hyacinth can produce 0.4 m^3 of biogas with a calorific value of 22 MJ/m^3. Aquatic weeds are a hazard in some waterways and have to be harvested, of necessity. The biofuel value is then a useful by-product [1].

13.2. Photosynthesis

Most living plants obtain their energy from sunlight. The basic metabolic processes are photosynthesis and respiration. In photosynthesis solar energy is converted into chemical energy in the plant and stored naturally as carbohydrates, including starch and cellulose. Solar energy is absorbed by the chlorophyll (i.e. the green material) and other plant chloroplast pigments, removing electrons from water molecules and liberating molecular oxygen. In generalised terms the photosynthetic reaction is

$$\text{sunlight absorbed by plant} + CO_2 + H_2O \rightarrow C_x(H_2O)_y + O_2 \tag{13.1}$$

The integer values x and y in (13.1) differ for different plants. Each reaction converts 114 kcal/mole (477 kJ/mole) of solar energy into stored chemical energy.

The carbohydrate may take the form of cane or beet sugar, $(C_{12}H_{22}O_{11})_n$, or more complex starches or cellulose, $(C_6H_{10}O_5)_n$. Cellulose and starch are the major end products of photosynthesis and most of it remains un-utilised, forming a large renewable source of chemicals and stored energy.

The biochemical reaction of photosynthesis, in (13.1), requires at least eight quanta of light energy. This usable input energy is equivalent to that of monochromatic light of wavelength 575 nm (0.575 μm). Eight quanta of 0.575 μm radiation have an energy content of 1665 kJ, giving a maximum theoretical photosynthetic efficiency of absorption of 477/1665 or 0.286 (28.6%). The actual theoretical efficiency is likely to be lower than this because experiments indicate that 8–10 quanta of energy may be needed to initiate the reaction.

Now only the visible part of the solar spectrum, Fig. 11.1, occupying wavelengths in the range 400–700 nm (0.4–0.7 μm), is used in photosynthesis. The photosynthetically active radiation (PAR) constitutes about 43% of the total incident radiation so that the maximum theoretical conversion efficiency from input radiation to plant energy content, under ideal conditions, is $0.43 \times 0.286 = 0.123$ or 12.3% [4].

When carbohydrates are ingested by animals the energy is released to do muscular work, to generate nerve impulses and to create proteins for the building of new cells [7]. Photosynthesis is therefore a process in which solar energy is used to convert inorganic raw materials into organic compounds.

Respiration is the reverse of the photosynthetic reaction. In the respiration of a plant or animal the combustion of carbohydrates and oxygen yields energy, carbon dioxide and water vapour. The respiration process of a plant uses typically about one-third of the energy stored by photosynthesis. The basic processes of plant photosynthesis and respiration are depicted in Fig. 13.2 [7].

The value 0.43 for the PAR could only be realised if there was complete and continuous radiation of a plant foliage. Such an optimally arranged leaf canopy is not normally realisable. In practice a plant can absorb, at best, about 80% of the PAR due to shading, shielding, overlap of growth, etc. Combining the photosynthetic efficiency with the absorption and respiration factors gives a maximum value of overall efficiency for the conversion of solar energy into stored chemical energy $0.123 \times 0.8 \times 0.667 = 0.066$ or 6.6%. The various stage efficiencies are summarised in Table 13.1 [4].

Many figures of photosynthetic efficiency have been suggested, based on experimental evidence. These are all lower than the theoretical overall maximum value

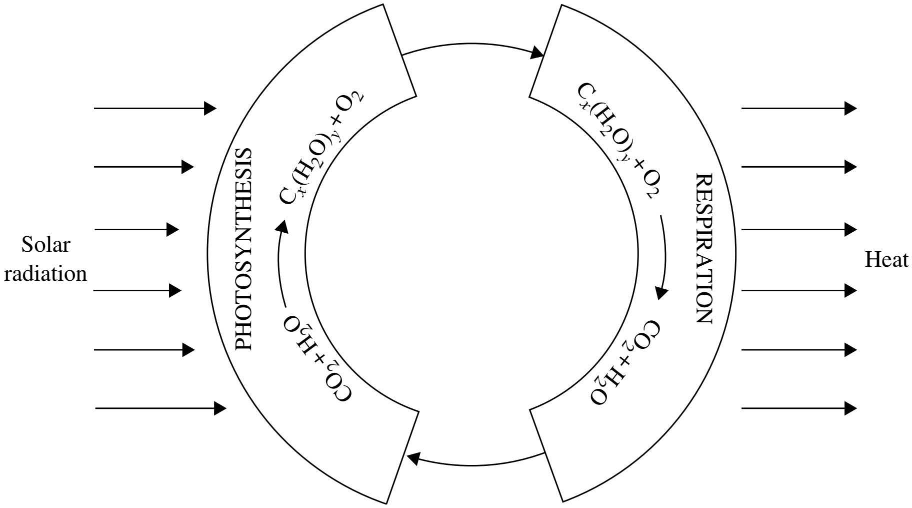


Fig. 13.2. Basic processes of photosynthesis and respiration [7].

Table 13.1. Maximum photosynthetic efficiency of land plants [4].

Parameter		Factor
Photosynthetically active radiation/total radiation		0.43
Maximum leaf absorption		0.8
Maximum efficiency of absorbed light conversion		0.286
(Photosynthesis–respiration)/photosynthesis		0.667
Overall efficiency $= 0.43 \times 0.8 \times 0.286 \times 0.667$	=	0.066

Table 13.2. Annual production and photosynthetic efficiencies of selected agricultural crops [4].

Crop	Location	Yield ($\mathrm{t\ ha^{-1}\ y^{-1}}$ dry wt)	Photosynthetic efficiency (%)
Temperate			
Sugar beet	Washington, USA	32	1.1
Wheat	Washington, USA	30 (grain)	0.1
Barley	UK	7 (grain)	0.3
Maize (C_4)	Japan	26	1.1
Subtropical			
Alfalfa	California, USA	33	1.0
Sugar beet	California, USA	42	1.2
Maize (C_4)	Egypt	29	0.6
Tropical			
Sugar beet	Hawaii (2 crops)	31	0.9
Cassava	Malaysia	38	1.1
Rice and sorghum (C_4) (multiple cropping)	Philippines	23 (grain)	0.7
Sugar-cane (C_4)	Hawaii	64	1.8
Maize (C_4)	Peru	26	0.8
Napier grass (C_4)	El Salvador	85	2.4

above of 6.6%. For optimum field conditions efficiencies in the range 3–5% are possible for limited periods. Typical annual conversion efficiencies are 0.5–1.3% for temperate crops and 0.5–2.3% for tropical and subtropical plants [4]. For large scale applications an average overall photosynthetic efficiency value of 1% has been suggested [7]. Figures for the photosynthetic efficiencies of selected agricultural crops are given in Table 13.2 [4].

13.3. Methods of Industrial Biomass Conversion

The principal processes for converting biomass material into usable forms of energy are shown in Fig. 13.3 [4]. Some liquid or gaseous biofuels such as methane can be obtained by several different processes, including biodegradation.

13.3.1. *Combustion*

Combustion is the best-known and probably the most efficient form of converting solid biomass to steam or electricity. Water pipes in incinerator walls can produce heat for CHP district heating or other co-generation purposes from forestry residues and industrial or urban wastes. In principle the energy system of biomass combustion is the same as that for fossil fuel combustion. A diagram of the appropriate stages, applied for the combustion of wood, is shown in Fig. 13.4. Fluidised-bed

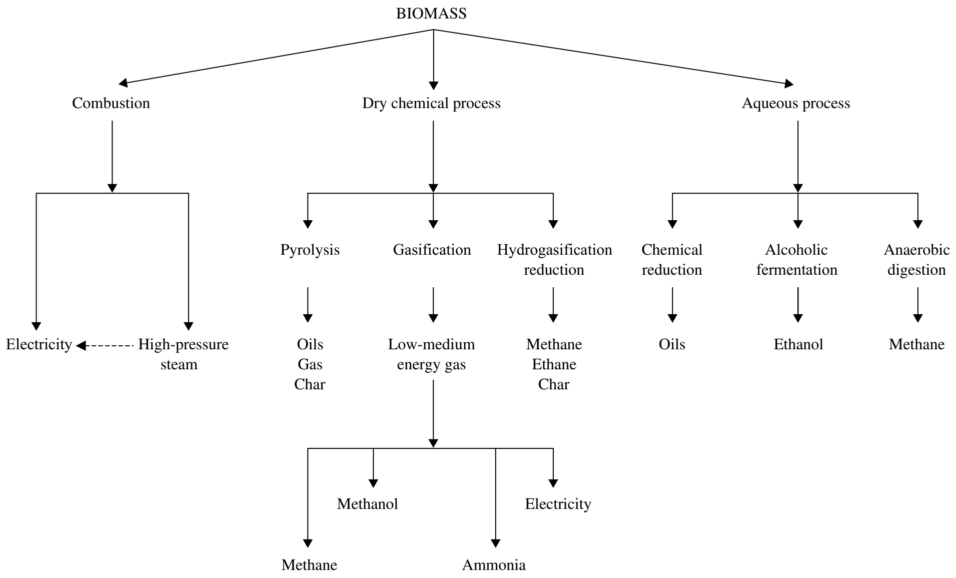

BIOMASS
Combustion
Dry chemical process
Aqueous process
Pyrolysis
Gasification
Hydrogasification reduction
Chemical reduction
Alcoholic fermentation
Anaerobic digestion
Electricity
High-pressure steam
Oils
Gas
Char
Low-medium energy gas
Methane
Ethane
Char
Oils
Ethanol
Methane
Methanol
Electricity
Methane
Ammonia

Fig. 13.3. Biomass energy conversion processes and products [4].

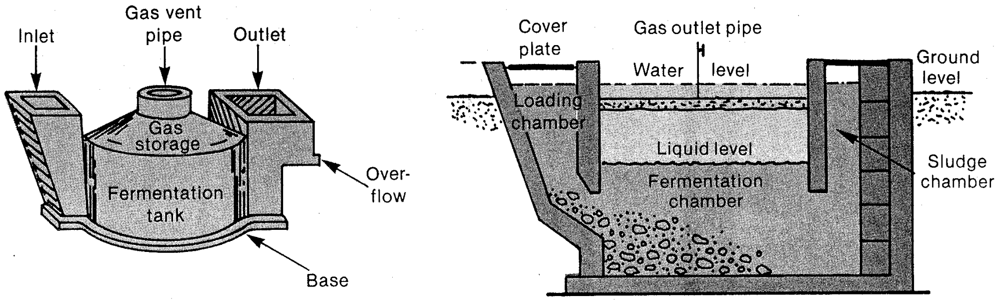

Inlet
Gas vent pipe
Outlet
Gas storage
Fermentation tank
Over-flow
Base
Cover plate
Gas outlet pipe
Water level
Loading chamber
Liquid level
Fermentation chamber
Ground level
Sludge chamber

Fig. 13.4. Chinese design of biogas plant [10].

boilers used in the UK coal industry and discussed in Sec. 4.6 of Chapter 4 have proven to be particularly appropriate for wood and wood wastes.

Industries that produce solid biomass residues such as rice husks, bagasse (cane sugar residue), corn cobs, cotton stalks and nut shells often burn their own residues as supplementary fuels.

Solid-biomass-fuelled generation systems are usually most competitive in relatively small sizes. As system size increases, the conventional alternative becomes cheaper, transport costs rise disproportionately and the amount of land needed to supply the biomass becomes very large. For example, with an average annual yield of 7 tons/hectare, almost 1500 hectares ($1500 \times 2.471 = 3706$ acres $= 5.8$ square miles) would be needed to produce 1 MW of power. This would constitute a very poor optional use of the land. In addition, industrial size solid-fuel boilers for wood (or coal) burning are of low efficiency and relatively high cost. If steam is not required as part of the process, then power requirements of below about 10 $\mathrm{MW_e}$ are better met by the use of pyrolytic gasification processes [9].

13.3.2. *Pyrolysis*

If organic matter is heated with insufficient oxygen to support combustion, the resulting action is called pyrolysis. It is common to heat in a non-oxygen atmosphere, such as nitrogen. For example, if wood is heated to about 250°C (480°F) the moisture and volatile materials evaporate, leaving carbon and inert materials in the form of charcoal (char). Utilisation of the gaseous and liquid products as well as the charcoal can result in an overall efficiency up to about 80%.

Charcoal can be transported and handled much more economically than an equivalent amount of wood. In many countries charcoal is the most widely used household fuel in urban (though not rural) areas. Charcoal stoves are more efficient than wood fires. There are many industrial applications that use charcoal in chemical reactions, including steel processing, cement manufacture, drying crops and metal smelting.

If organic material is heated between 500°C and 900°C at ordinary pressures in the absence of oxygen, then methanol is produced. This is widely used as an automobile fuel additive [1].

13.3.3. *Gasification of biomass*

The gasification of solid biomass is carried out in the presence of limited air or oxygen but at higher temperatures and/or pressures than for pyrolysis. The low energy "producer" gas can be intermediate in several production processes and contains carbon monoxide, hydrogen, carbon dioxide and methane. If the gaseous phase is condensed, followed by distillation to 98% purity, then methanol is formed via a catalytic reforming process. Another product realisable is ammonia, used in the manufacture of chemical fertilisers. Producer gas can also be used in combined cycle gas turbine-steam cycle electricity generation systems [4]. Wood and charcoal gasifiers were used in Europe during the 1930s and 1940s (i.e. including the gasoline-starved years of the Second World War) to fuel motor vehicle engines. Such systems were very demanding of maintenance, even under the most favourable conditions [10]. Producer gas typically contains about 25% carbon dioxide and 15% hydrogen, so that its fuel value is about one-sixth that of natural gas.

Biomass can be converted to methane and ethane by reduction with hydrogen at 540°C and 6.9×10^6 Pa pressure. This process is limited in usefulness by the fact that the hydrogen itself is a premium fuel [4].

Gasification technologies for solid biomass fuels, including solid wastes, have a number of potential environmental problems. The quantity and mix of resulting air pollutants depend on the gas-producing technology and on the chemical content of the initial feedstock. There is likely to be formation of ammonia (NH_3), hydrogen sulphide (H_2S), hydrogen cyanide (HCN), dicarbon sulphide (COS), as well as phenols. Leaks of raw gas would be a hazard in the immediate locality.

Most biomass feedstocks used in gasification processes have concentrations of trace elements such as potassium, magnesium, sodium, iron, boron, barium, cadmium, chromium, copper, lead, strontium and zinc. These levels of chemical concentration, plus fly-ash and sulphur content, are much lower than in coal combustion. Feedstock derived from farm waste may be contaminated with pesticides, fertilisers and soil [10].

In biomass gasification water is present in the initial feedstock and is also formed during combustion. Biomass storage sites can also leach polluted rain water. The safe disposal of effluent water is part of the overall biomass safety problem.

13.3.4. *Liquid and gaseous fuels from biomass*

13.3.4.1. *Chemical reduction*

Fuel oils of varying compositions can be obtained by the chemical and physical reduction of aqueous biomass, Fig. 13.3. For example, carbon monoxide, steam and a slurry of cellulosic waste react together at 250–400°C and 13.8–27.6 $\times 10^6$ Pa pressure, with an alkaline catalyst, to yield a fuel oil of approximate formula $C_{11}H_{19}O$ with an energy content of 40 MJ/kg [4]. This compares favourably with all of the types of coal in Table 4.1 of Chapter 4.

13.3.4.2. *Aerobic (alcoholic) fermentation*

The aerobic fermentation process uses biomass materials containing starches and simple sugars. Starch feedstocks are mainly grain crops and cereals but also include root plants like potatoes. Sugar feedstocks include cane and beet sugar, sorghum and artichokes. Fermentation produces ethyl alcohol or ethanol, which is the intoxicant ingredient in beer, wine and spirits [10].

Ethanol is a relatively clean burning fuel that can be used as a substitute for gasoline (petrol) in modified internal combustion engines or as a non-lead, octane-enhancing gasoline additive. The major producers of ethanol include Brazil, the USA and France. In Brazil many cars use ethanol in place of petrol. An alcohol-powered car uses a smaller engine, with smaller cooling and exhaust systems, than a petrol car [8].

In the UK many formerly green fields now grow crops of bright yellow oilseed rape or blue linseed. Rape grain can be processed into the biodegradable chemical called rape methylester, which is similar to diesel fuel but much more expensive to produce. Valuable by-products of the process include protein-rich animal feed and glycerine [11].

13.3.4.3. *Anaerobic digestion to produce biogas*

In the anaerobic ("without oxygen") decomposition of organic materials, bacteria consume the material in an airtight container, called a digester. The bacteria may be in the original charge material, such as animal manure, or it may be intentionally introduced to facilitate the process. The digester operates at a working temperature in the range 95–140°F and yields a mixture of gases often referred to as "biogas". When this gas occurs naturally due to rotting vegetation it is called "swamp gas". The same biochemical process is used in some forms of sewage treatment.

Biogas contains 50–70% methane, similar to natural gas, with the remainder mostly carbon dioxide. It has the heat value of its methane component, 39 MJ/m^3, as shown in Table 13.3 [4], and can be used directly for heating or in internal combustion engines. In the developing countries there is a lot of interest in biogas units for household fuel, for the improvement of sanitation and to improve the fertiliser value of animal dung and other organic wastes [9].

The anaerobic microbiological digestion process is especially well adapted to slurry-type wastes. Such processes have been used for many years to treat sewage and its by-products as fertilisers. They can be used as waste treatment operations to reduce pollution hazards and nuisance odours. An additional benefit is that a fertiliser rich in nitrogen is retrieved from the digested slurry as a by-product. Furthermore, the residual from the process can be returned to the land, unlike other biomass conversion processes, which almost totally destroy the input material [10].

There are many forms of anaerobic digester design, ranging from the small domestic size to large industrial systems. In China, for example, over seven million small digestion systems have been installed, mostly family-sized units, to partially meet the cooking, space heating and lighting demands of small rural communities [8, 9]. A diagram of the Chinese design is given in Fig. 13.4 [10]. In the USA the majority of biogas installations are used to collect gaseous emissions from landfill waste deposits. Because biogas units operate at low pressure, the pipeline distribution is generally limited to a restricted area. The small hydrogen sulphide component is corrosive to metal. However, with suitable adjustments to the burners, most appliances made for natural gas or bottled gas can be adapted for use with biogas [9].

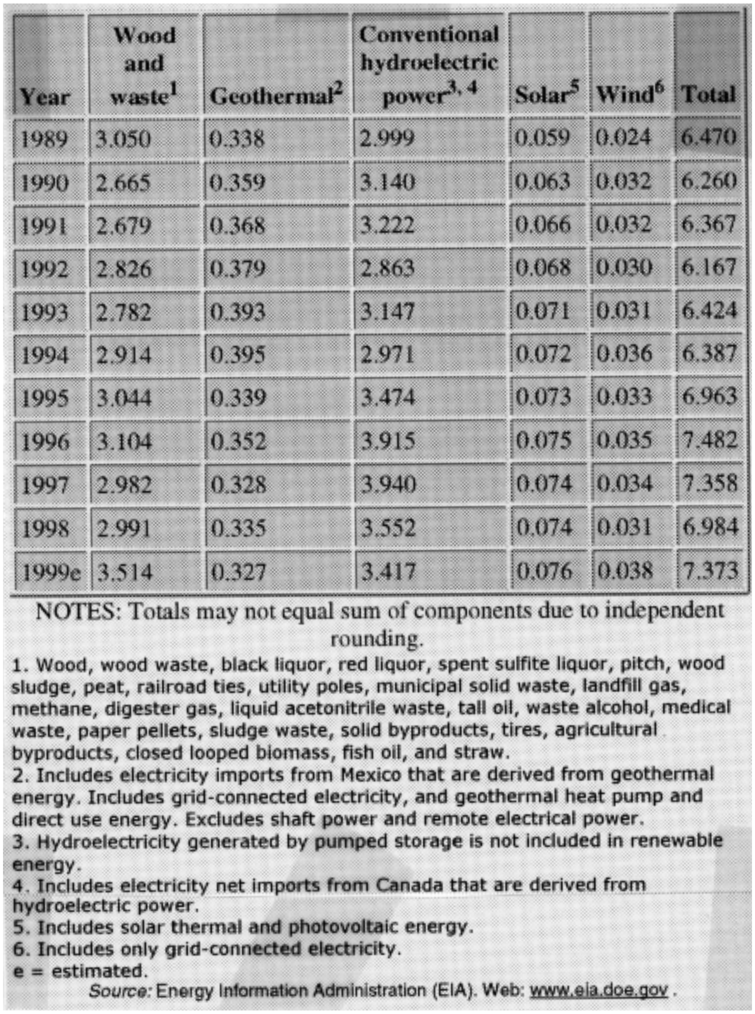
13.4. Wood as a Fuel

Most poor people in the developing countries use wood as a cooking fuel. In the early 1980s it was estimated that "more than 90% of the wood cut in Africa — five million acres a year — is burnt as fuel" [12]. The World Bank has estimated that between a half and one billion people use agricultural or animal wastes as fire fuel [13, 14]. Moreover, a lot of this fuel is used inefficiently in open fires with cooking utensils sitting on it or suspended over it. The efficiency of use would be increased by a factor of 4–5 by enclosing the fire, regulating the flow of air into

Table 13.3. Bioconversion processes and products [4].

Process		Initial product	Final product
	Anaerobic digestion	Biogas: $CH_4$2 : 1CO_2 (22–28 MJ m^{-3})	Methane (38 MJ m^{-3})
Aqueous	Alcohol fermentation		Ethanol (19 MJ l^{-1})
	Chemical reduction		Oils (35–40 MJ kg^{-1})
Dry Thermochemical	Pyrolysis		Pyrolytic oils (23–30 MJ kg^{-1}) Gas (8–15 MJ m^{-3}) Char (19–31.5 MJ kg^{-1})
	Gasification	Low-medium energy gas (7–15 MJ m^{-3})	Methane (38 MJ m^{-3}) Methanol (16.9 MJ l^{-1}) Ammonia Electricity (3.6 MJ kW h^{-1})
	Hydrogasification		Methane (38 MJ m^{-3}) Ethane (70.5 MJ m^{-3}) Char (19–31.5 MJ kg^{-1})
Direct combustion of:		High-pressure steam	High-pressure steam
Wood chips (18.6–20.9 MJ kg^{-1} dry wt)			Electricity (3.6 MJ kW h^{-1})
Sugar-care bagasse (9.5 MJ kg^{-1})			
Cereal straw (16–17 MJ kg^{-1})			
Organic refuse (13.2 MJ kg^{-1})			
Biophotolysis (see Chapter 7)			Hydrogen (12.7 MJ m^{-3})

Table 13.4. Renewable energy consumption (quadrillion BTU) in the USA, by source, 1989–1999 [17].



Year	Wood and waste[1]	Geothermal[2]	Conventional hydroelectric power[3, 4]	Solar[5]	Wind[6]	Total
1989	3.050	0.338	2.999	0.059	0.024	6.470
1990	2.665	0.359	3.140	0.063	0.032	6.260
1991	2.679	0.368	3.222	0.066	0.032	6.367
1992	2.826	0.379	2.863	0.068	0.030	6.167
1993	2.782	0.393	3.147	0.071	0.031	6.424
1994	2.914	0.395	2.971	0.072	0.036	6.387
1995	3.044	0.339	3.474	0.073	0.033	6.963
1996	3.104	0.352	3.915	0.075	0.035	7.482
1997	2.982	0.328	3.940	0.074	0.034	7.358
1998	2.991	0.335	3.552	0.074	0.031	6.984
1999e	3.514	0.327	3.417	0.076	0.038	7.373

NOTES: Totals may not equal sum of components due to independent rounding.

1. Wood, wood waste, black liquor, red liquor, spent sulfite liquor, pitch, wood sludge, peat, railroad ties, utility poles, municipal solid waste, landfill gas, methane, digester gas, liquid acetonitrile waste, tall oil, waste alcohol, medical waste, paper pellets, sludge waste, solid byproducts, tires, agricultural byproducts, closed looped biomass, fish oil, and straw.
2. Includes electricity imports from Mexico that are derived from geothermal energy. Includes grid-connected electricity, and geothermal heat pump and direct use energy. Excludes shaft power and remote electrical power.
3. Hydroelectricity generated by pumped storage is not included in renewable energy.
4. Includes electricity net imports from Canada that are derived from hydroelectric power.
5. Includes solar thermal and photovoltaic energy.
6. Includes only grid-connected electricity.

e = estimated.

Source: Energy Information Administration (EIA). Web: www.eia.doe.gov .

the stove and venting through a chimney [9]. Many governments and aid agencies all over the world are addressing the need for better and different forms of wood-burning stoves. For fuelwood to satisfy this need, greatly increased planting levels would be required all over the developing world [9]. Moreover, deforestation and desertification is widespread and increasing in Africa. For example, the southern edge of the Sahara desert has moved 100 km south in 17 years [1].

In medieval Europe wood was the main fuel and the whole continent, including Great Britain, was heavily forested. Between 1550 AD and 1700 AD, the population of Britain doubled and the demand for timber resulted in massive deforestation. A transition took place from wood cutting to coal mining as the main source of heat. This changed the economic history of Britain, then of the rest of Europe and finally of the world. It led to the Industrial Revolution, which started in Britain around 1780 AD, with the expansion of manufacturing industries and the exploitation of untapped natural resources [15].

By the middle of the 19th century, wood was the principal fuel in the USA. By 1900 AD it provided 25% of the country's annual energy, but this usage had fallen to 1.5% in 1976. Most of the 1.5% came from the forest products industry, which burns tree wastes. The use of biomass, typically in wood-burning stoves, is increasing in North America and now represents about 4% of energy use. This still lags far behind wood heating in Sweden and Finland, where, in 1981, 8% and 15% respectively of the energy needs were met by wood [16]. More than 300 US power plants use biomass to produce 5000 $\mathrm{MW_e}$ of electricity.

The use of wood and waste in the USA is now of the same order of magnitude as the use of conventional hydroelectric power for electricity generation, Table 13.4. It is significant that in 1999 wood and waste provided about 100 times the electricity generation capability of wind energy, which is about 50 times the contribution of solar energy [17]. Comparable data for the UK is shown in Table 13.9.

Various options for the use of wood as a biomass fuel are included in Table 13.5. The direct combustion of wood to produce steam or oil represents one of the cheapest options available [4]. In comparison with coal, wood fuel is bulkier and contains more volatile constituents, leading to the need for less expensive combustion plants.

If combusted properly wood is far less polluting than either coal or oil, particularly with regard to sulphur emissions [18]. It is significant to note that the carbon dioxide (CO_2) released on wood combustion is the same as the carbon dioxide taken

Table 13.5. Comparative costs for various biomass conversions per unit of energy output [4].

Process	Comparative cost rating
Wood to char and oil for direct combustion	1.0–1.3
Steam production from wood via direct combustion	1.1–1.2
Medium-energy gas production from cattle manure via anaerobic digestion	1.5–3.3
Wood to oil via catalytic liquefaction	2.0
Substitute natural gas production from cattle manure via anaerobic digestion	2.2–5.3
Substitute natural gas production from wood gasification (oxygen-blown reactor)	2.4–2.9
Wood to methanol via gasification (oxygen-blown reactor)	2.9–3.7
Ammonia from wood via gasification (oxygen-blown reactor)	3.3–7.0
Wheat straw to medium-energy gas via anaerobic digestion	4.9–8.8
Electricity generation from wood via direct combustion	6.1–6.9
Algae to ethanol via acid hydrolysis and fermentation	7.0–9.9
Corn straw to ethanol via enzymatic hydrolysis and fermentation	7.4–16.2
Kelp to substitute natural gas via anaerobic digestion	7.7–8.3
Sugar-cane to ethanol via fermentation	11.9
Wheat straw to ethanol via enzymatic hydrolysis and fermentation	19.5

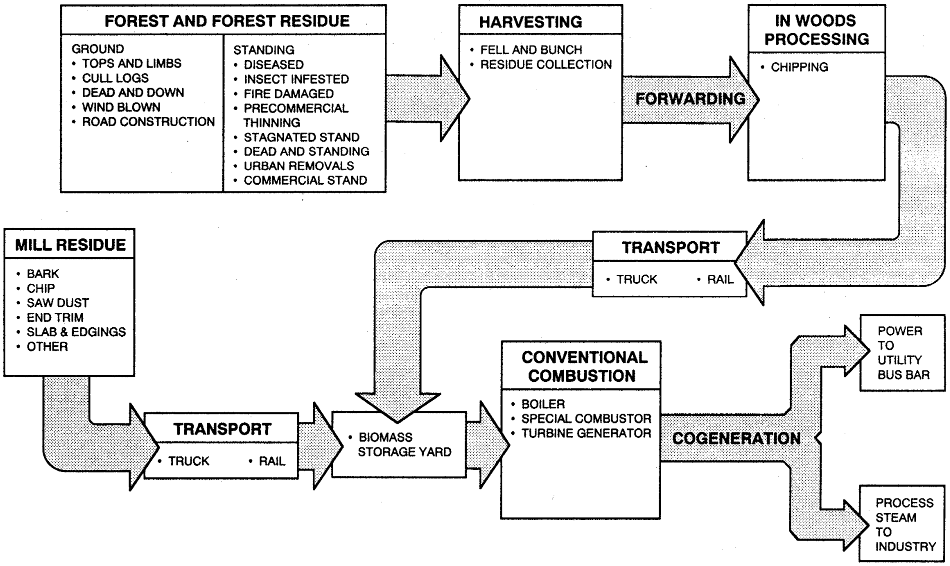

FOREST AND FOREST RESIDUE
GROUND
• TOPS AND LIMBS
• CULL LOGS
• DEAD AND DOWN
• WIND BLOWN
• ROAD CONSTRUCTION
STANDING
• DISEASED
• INSECT INFESTED
• FIRE DAMAGED
• PRECOMMERCIAL THINNING
• STAGNATED STAND
• DEAD AND STANDING
• URBAN REMOVALS
• COMMERCIAL STAND
HARVESTING
• FELL AND BUNCH
• RESIDUE COLLECTION
FORWARDING
IN WOODS PROCESSING
• CHIPPING
TRANSPORT
• TRUCK
• RAIL
MILL RESIDUE
• BARK
• CHIP
• SAW DUST
• END TRIM
• SLAB & EDGINGS
• OTHER
TRANSPORT
• TRUCK
• RAIL
• BIOMASS STORAGE YARD
CONVENTIONAL COMBUSTION
• BOILER
• SPECIAL COMBUSTOR
• TURBINE GENERATOR
COGENERATION
POWER TO UTILITY BUS BAR
PROCESS STEAM TO INDUSTRY

Fig. 13.5. Network for wood fuel electricity generation [9].

up during the plant growth. Wood can therefore be described as carbon-dioxide-neutral. This means that when wood is burned in preference to a fossil fuel, there is a net reduction of atmospheric carbon dioxide and therefore a lower contribution to the production of greenhouse gases. But note that wood (trees) has taken in CO_2 over many, many years whereas burning wood releases CO_2 quickly — this alters the carbon dioxide equilibrium of the atmosphere.

In the UK, research is now under way to look into the possibility of building wood-fuelled electricity-generating stations. Year-old trees, such as willows, are cut down near to the ground, causing them to throw up around six new shoots, which grow rapidly over the next 3–5 years. This is known as coppicing. The harvested coppice wood can be dried, chipped and used as fuel.

The successful and economic use of wood as a primary fuel, whether from conventional forestry or from energy forestry, depends on a chain consisting of resource, harvesting, storage and transport [19]. A detailed flow graph of the processing of wood fuel to steam or electricity generation is given in Fig. 13.5.

13.5. Energy from Wastes

All human and industrial processes produce waste. In the industrial countries the amount of municipal solid waste derived from domestic, commercial and industrial sources increases every year. Data for the USA, from 1960 to 1999, is shown in Fig. 13.6 [20].

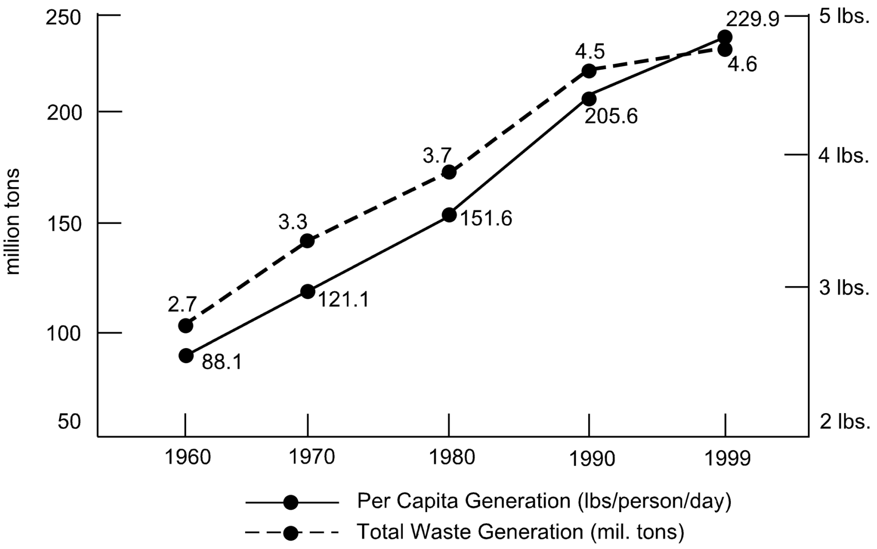


Fig. 13.6. US municipal solid waste generation, 1960–1999 [20].

Wastes that can form sources of biofuels include domestic refuse, industrial wastes, agricultural wastes, forestry residues, sewage and industrial effluents. It is highly desirable that the recovery of energy from waste should form part of an integrated approach to waste management, designed to maximise waste recycling and reclamation. Recycling prevents the emission of many greenhouse gases and water pollutants, saves energy, supplies valuable raw materials to industry, creates jobs, stimulates the development of greener technologies, conserves resources for the future and reduces the need for new landfills and combustors (incinerators). In 1996, recycling of solid waste in the USA prevented the release of 33 million tons of carbon into the air — roughly the amount emitted annually by 25 million cars [20]. The US recycling rates of selected materials for 1999 are shown in Fig. 13.7.

Using wastes as a direct source of energy can be highly cost-effective, especially if the alternative disposal cost is discounted.

Wastes do have certain disadvantages when used as fuel sources. They may be difficult to handle and process and generally they have low energy density. Some wastes may be contaminated with non-fuel materials. Also, it may be necessary to transport the waste from its source to a conversion site [18].

13.5.1. *Solid waste disposal in landfill sites*

Large municipal or industrial landfills produce gas that can be tapped to generate electricity. Microorganisms that live in organic materials such as food wastes, paper or yard clippings cause these materials to decompose. This produces landfill gas, typically comprised of roughly 60% methane and 40% carbon dioxide, similar to the biogas described in Sec. 13.3.4.3.

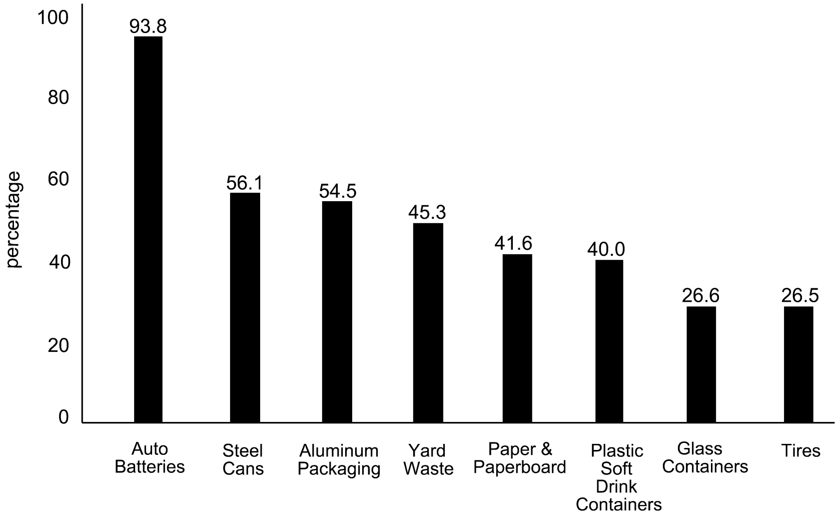


Fig. 13.7. US recycling rates of selected materials, 1999 [20].

Table 13.6. Composition of typical UK municipal solid waste [11].

Category	Per cent	Calorific value (MJ/kg)
Paper and cardboard	30.5	14.6
Food waste	24	6.7
Metal	7.8	—
Glass	11.2	—
Dust and cinders	9.0	9.6
Textiles	4.9	16
Leather, rubber	8.3	17.6–37
Miscellaneous	4.3	17.6
Total	100%	

Table 13.7. Composition of USA municipal solid waste, 1999 [20].

Category	Per cent
Paper	38.1
Yard waste	12.1
Food waste	10.9
Plastics	10.5
Metals	7.8
Rubber, leather and textiles	6.6
Glass	5.5
Wood	5.3
Other	3.2
Total	100%

Landfill gas (LFG) is collected from landfills by drilling "wells" into the landfills, and collecting the gases through pipes. Once the landfill gas is processed, it can be combined with natural gas to fuel conventional combustion turbines or used to fuel small combustion or combined cycle turbines. Landfill gas may also be used in fuel cell technologies, which use chemical reactions to create electricity, and are much more efficient than combustion turbines [21].

In a highly developed society like Great Britain or the USA, solid waste from all sources is produced at the rate of about one tonne per person per year [5, 18].

Most domestic waste is solid in form. The constituent proportions typical of UK municipal waste are shown in Table 13.6 [11]. Corresponding data for the USA in 1999 is given in Table 13.7 [20].

Each year the UK produces 28 million tonnes of solid domestic waste plus a similar amount of industrial waste. Solid wastes are usually disposed of either by burning or by burial in landfill sites. The majority of the domestic waste produced in the UK is not burned but is buried in about 5000 landfill sites. At the end of 1990 there were 33 landfill gas schemes in operation in the UK, including 18 MW_e of electricity generation. By 1995 there were 50 gas-producing sites in operation and an estimated further 400 sites that could be used. The largest current site in the UK produces 3500 m^3 of methane per hour to make steam for use in paper production. A diagrammatic representation of a landfill gas system is given in Fig. 13.8 [11].

As of May 2001, over 325 landfill gas recovery and utilisation projects were operational in the USA. The US Environmental Protection Agency (EPA) estimates that about 700 other landfill sites present attractive opportunities for project development [22].

The venting of landfill gases poses some environmental problems. Within the site vicinity there may be objectionable odours. Uncontrolled discharges from landfill sites account for an estimated 21% of UK methane emissions. If the landfill gas

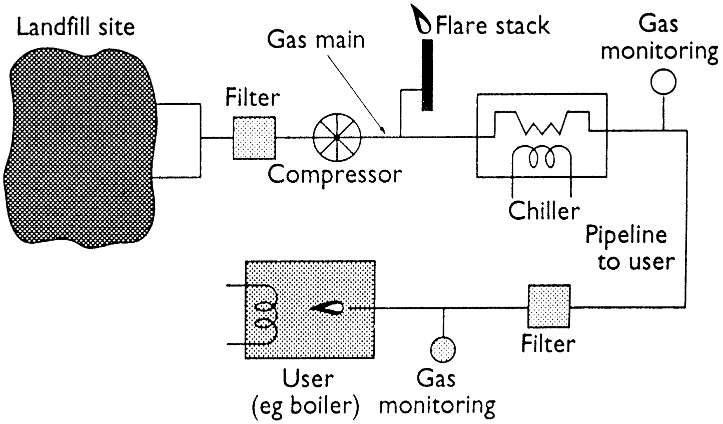


Fig. 13.8. Production of landfill gas [11].

can be used as a fuel its own methane discharge is minimal and it also reduces the carbon dioxide that would be emitted by the equivalent fossil fuels [18].

In the USA the EPA requires all large landfills to install collection systems at landfill sites to minimise the release of methane, a major contributor to global climate change. While new EPA regulations require gathering and flaring of methane from large landfill operations, small landfills, which fall outside the federal agency's jurisdiction, may amount to as much as 40% of the methane generated by landfills nationwide.

Landfill gas generators produce nitrogen oxide emissions that vary widely from one site to another, depending on the type of generator and the extent to which steps have been taken to minimise such emissions. Combustion of landfill gas can also result in the release of organic compounds and trace amounts of toxic materials, including mercury and dioxins, although such releases are at levels lower than if the landfill gas is flared [22].

There are few water impacts associated with landfill gas power plants. Unlike other power plants that rely upon water for cooling, landfill gas power plants are usually very small, and therefore pollution discharges into local lakes or streams are typically quite small [22].

13.5.2. *Solid waste disposal using municipal incinerators (combustors)*

The burning of municipal solid waste can generate energy while reducing the amount of waste by up to 90% by volume and 75% by weight. In the USA in 1999, there were 102 incinerators with energy recovery capability, having the capability to burn 96,000 tons of waste per day [20].

For combustion in a modern waste incinerator the refuse can be first sorted to separate out materials such as glass for recycling. The remainder is shredded to convert the burnable component into refuse-derived fuel pellets [18].

The pellets burn like wood but produce less heat than coal and leave more ash. Modern municipal waste incinerators produce no smoke and reduce the bulk of the waste to about one eighth. Some wastes, such as synthetic polymers (e.g. plastics produced from petrochemicals), produce toxic gases on combustion and these have to be safely contained within the incineration process.

General industrial waste consists mainly of paper, cardboard, wood and plastics. It contains a lower moisture and lower ash content than municipal waste, making combustion easier to control, and is less contaminated with non-fuel ingredients. Special forms of industrial waste such as batteries, motor tyres, poultry litter and hospital wastes are potential hazards and require special forms of treatment but are all useful biofuels for combustion systems [18].

Refuse incineration in municipal plants for energy recovery is a relatively new but growing technology in the UK, as illustrated in Table 13.8 [11] and Table 13.9 [23].

Table 13.8. Refuse incineration in the European Community [11].

Country	Number of plants	Total waste processed (tonnes/day)	Energy recovered Hot water	Steam	Electricity
Belgium	6	3650	3	1	2
Denmark	63	9100	58	5	0
Eire	0	0	0	0	0
France	33	13,700	10	21	9
Germany	43	21,780	13	27	29
Greece	0	0	0	0	0
Italy	6	3250	6	0	1
Luxembourg	2	800	0	0	2
The Netherlands	5	5670	1	1	4
Portugal	0	0	0	0	0
Spain	4	1350	0	4	2
UK	7	3500	5	0	3
Total	169	62,800	96	60	52

Table 13.9. Renewables energy sources in the UK [23].

Total use renewables	Thousand tonnes of oil equivalent 1990	1998	1999	2000
Active solar heating	6.4	9.4	10.0	10.5
Onshore wind	0.8	75.4	73.1	81.3
Hydro	447.7	440.0	460.9	439.1
Landfill gas	79.8	402.4	572.0	731.2
Sewage sludge digestion	138.2	180.6	188.8	161.3
Wood	174.1	641.1	571.9	502.8
Straw (for heat)	71.7	71.7	717	71.7
Municipal solid waste	160.0	574.0	579.6	636.2
Other biofuels	24.0	197.3	240.9	362.7
Total	1,102.7	2,592.7	2,769.8	2,996.8

In the UK, in 2000, biofuels accounted for 82% of renewable energy sources, Table 13.9, with most of the remainder coming from large scale hydroelectricity production. Hydro accounts for 15% and wind power contributes 2.5%. Of the almost 3 million tonnes of oil equivalent of primary energy use accounted for by renewables, 2.2 million tonnes was used to generate electricity and 0.8 million tonnes to generate heat. The largest and growing components are seen to be landfill gas and municipal solid waste. There has been much consideration of the relative merits of landfill gas extraction and municipal solid waste incineration. For example:

> "A Royal Commission on Environmental Pollution in Great Britain studied greenhouse emissions from both landfills and incinerators (Royal Commission, 1993). They reported that incinerating one million tonnes of municipal garbage produces net emissions of

> 15,000 tonnes of carbon in the form of carbon dioxide, whereas landfilling it with energy recovery produces emissions of greenhouse gases equivalent to 50,000 tonnes of carbon as carbon dioxide. Thus, even with gas collection and burning, landfills have a worse impact on global warming than incinerators." [24]

Nevertheless there is widespread opposition to the siting and installation of municipal incinerators, both in Europe and in the USA. The misgivings are chiefly concerned with environmental safety and the release of contaminated gases and fluids.

13.5.3. *Worked examples on solid waste incineration*

Example 13.1

A ton of municipal refuse contains the proportions of material indicated in Table 13.6. Calculate the calorific value if all the energy is recoverable. What is the equivalent energy in (a) kWh? (b) tonnes of oil?

$$1 \text{ ton} = 2240 \text{ lb} = \frac{2240}{2.2046} = 1016 \text{ kg} = 1.016 \text{ tonnes}$$

Applying the percentage proportions in Table 13.6 and multiplying by the appropriate calorific value gives the data of the following table:

Material	Weight in kilogrammes	Calorific value (MJ)
Paper	$0.305 \times 1016 = 309.9$	$309.9 \times 14.6 = 4524.5$
Food waste	$0.24 \times 1016 = 243.8$	$243.8 \times 6.7 = 1633.5$
Metal	$0.078 \times 1016 = 79.25$	$79.25 \times 0 = 0$
Glass	$0.112 \times 1016 = 113.8$	$113.8 \times 0 = 0$
Dust, cinders	$0.09 \times 1016 = 91.44$	$91.44 \times 9.6 = 877.8$
Textiles	$0.049 \times 1016 = 49.8$	$49.8 \times 16 = 796.5$
Leather, rubber, plastic	$0.083 \times 1016 = 84.3$	$84.3 \times 25^* = 2108.2$
Miscellaneous	$0.043 \times 1016 = 43.7$	$43.7 \times 17.6 = 768.9$
		Total 10,709 MJ

*Estimated value

From Table 1.5 of Chapter 1, 3.6 MJ ≡ 1 kWh.

(a) $\therefore$ 1 ton refuse $\equiv \frac{10709}{3.6} \equiv 2974.7$ kWh

1 tonne of oil $\equiv 4000$ kWh

(b) $\therefore$ 1 ton refuse $\equiv \frac{2974.7}{4000} \equiv 0.744$ tonne of oil

In practical terms, perhaps 20–50% of the energy in the refuse might be reclaimable.

Then:

1 ton of refuse yields the equivalent of about
750 kWh or 0.19 tonne of oil minimum to
1500 kWh or 0.38 tonne of oil maximum.

Example 13.2

The estimated "energy cost" of collecting and disposing of municipal waste is about 5000 MJ/tonne [5]. Does the energy value of 1 ton of waste justify the collection in energy terms?

The total energy value of 1 ton of waste in Example 13.1 is 10,709 MJ. This is more than twice the specified energy cost of collection and disposal.

The actual energy profit will depend on what proportion of the maximum potential value (10,709 MJ) is extractable. If 50% energy is available there will be a small energy profit. But part of the collection and disposal cost is for public health and social reasons and has to be undertaken anyway. Any energy profit is a bonus.

13.5.4. *Liquid and gaseous wastes*

Large scale liquid and gaseous wastes from industry are often processed at the producer sites. This permits the retrieval of salvageable materials and contributes to energy costs when the residue is burned. Liquid wastes from domestic sources are usually poured down the drain.

Sewage disposal is an issue of concern in the UK. Many communities adjacent to rivers, lakes or the sea eject raw sewage directly into the water. This poses problems of water pollution. It also eliminates the possibility of sewage treatment to minimise the effluent and to obtain useful sewage gases, such as methane.

13.6. The Fuel Cell

A fuel cell uses the gases hydrogen and oxygen as energy sources to produce electricity and water. It consists of two electrodes which enclose an electrolyte, Fig. 13.9.

Hydrogen fuel is fed into the "anode" of the fuel cell. Oxygen (or air) enters the fuel cell through the cathode. Encouraged by a catalyst, the hydrogen atom splits into a proton and an electron, which take different paths to the cathode. The proton passes through the electrolyte. The electrons create a separate electric current that can be utilised before they return to the cathode, to be reunited with the hydrogen and oxygen in a molecule of water [25, 26].

A fuel cell system usually includes a "fuel reformer" that can utilise the hydrogen from any hydrocarbon fuel, including methanol, ethanol, natural gas, liquid propane, gasified coal, gasoline and diesel fuel. Input energy can also be supplied by hydrogen derived, via methane, from biomass, wind and solar renewable sources,

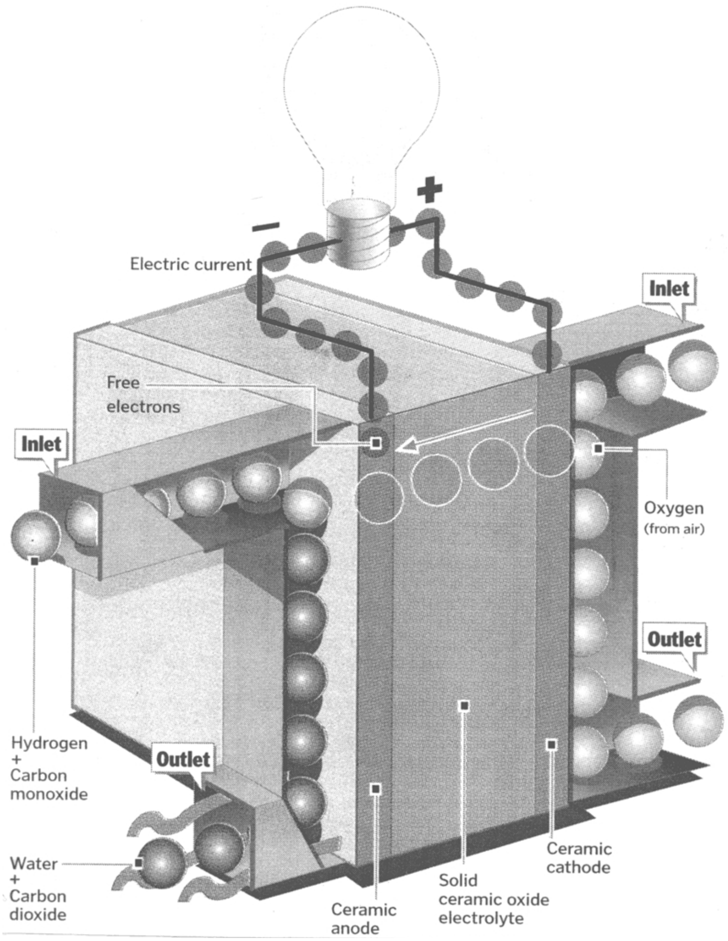

+
−
Electric current
Inlet
Free electrons
Inlet
Oxygen (from air)
Outlet
Hydrogen + Carbon monoxide
Outlet
Water + Carbon dioxide
Ceramic cathode
Solid ceramic oxide electrolyte
Ceramic anode

Fig. 13.9. Basic principle of the fuel cell [26].

including gas from landfills. Since the fuel cell relies on chemistry and not combustion, emissions from this type of system are much smaller than emissions from the cleanest fuel combustion processes.

Serious interest in the fuel cell as a practical and reliable source of electricity began in the 1960s in the US space program. Fuel cells furnished power for the *Gemini* and *Apollo* spacecraft and still provide electricity and water for the space shuttle.

Fuel cells are ideal for home power generation, either connected to the electricity grid to provide supplemental power and back-up or installed as a grid-independent generator for on-site service in areas that are inaccessible by power lines. Since fuel cells operate silently, they reduce noise pollution as well as air pollution and the waste heat from a fuel cell can be used to provide hot water or space heating.

Fuel cell automobiles are an attractive advance from electric battery-powered and hybrid (i.e. battery plus gasoline power) vehicles. They offer the advantages of battery-powered vehicles but can also be refuelled quickly and could go longer between refuelling.

Fuel cells utilising pure hydrogen as a fuel would be zero emission vehicles. Those using other fuels would produce near zero emissions. They are also more efficient than "grid"-powered battery vehicles. In addition, fuel cell cars could produce fewer "system-wide" releases of greenhouse gases — taking into account all emissions associated with resource recovery, fuel processing and use. Studies in the USA by General Motors and by Ford noted that fuel cell car engines could be built for about the same price as an internal combustion engine. The energy efficiency of fuel cells also makes them an attractive alternative for automakers. Many automotive manufacturers are racing to be the first to bring a fuel cell vehicle to the marketplace. US automakers and component suppliers are spending billions of dollars to drive fuel cell technology towards commercialisation. Some are concentrating on using pure hydrogen, while others are trying to find new ways to use gasoline-like hydrocarbons [25].

At present (2002) hydrogen is a more expensive fuel than conventional fossil fuels. A US company offers commercial fuel cell power plants for about $3000 per kilowatt. At that price the units are competitive in high value, "niche" markets and in areas where electricity prices are high and natural gas prices are low. A study by Arthur D. Little, Inc., has predicted that when fuel cell costs drop below $1500 per W they will achieve market penetration nationwide in the USA. Several companies are now selling small units for research purposes. Fuel cells will have to be much cheaper to become commercial in passenger vehicles. Conventional car engines cost about $3000 to manufacture in the USA. More research is needed to bring the cost of fuel cell systems down to that level [25]. The widespread use of fuel-cell-driven automobiles would dramatically reduce the world oil consumption and the emissions from its use.

13.7. Problems and Review Questions

13.1. What are the principal disadvantages of the use of land for intensive biofuel growth?

13.2. Describe the process of photosynthesis in plants. In particular, what are the input forms of energy of the photosynthetic process?

13.3. Enumerate the stages of the photosynthetic process to show that the maximum efficiency under ideal conditions from input radiation to plant energy storage is 6.6%.

13.4. What are the practical values of photosynthetic efficiency in (a) temperate locations and (b) tropical locations?

13.5. What is the nature and purpose of the bright yellow crop now seen in many English fields?

13.6. What is the chief constituent of the biogas in anaerobic digester systems? Why are such systems so abundant in the developing countries?

13.7. What are the chief advantages of wood as a source of fuel?

13.8. In what sense can the burning of wood be described as "carbon-dioxide-neutral"?

13.9. What are the advantages and disadvantages of burning plastics as a biofuel?

13.10. How would the wider use of biofuels affect the appearance of the British countryside?

13.11. How would the contents of refuse collection in Victorian England or 19th century USA compare with the present day?

13.12 In the period 1990–2000, how did the proportions of (a) landfill gas, (b) wood, (c) municipal solid waste, of the renewable energy sources change in the UK?

13.13 In the period 1989–1999, how did the proportions of (a) wood and waste, (b) conventional hydro power, (c) solar energy, (d) wind energy, of the renewable energy consumption change in the USA?

13.14 Compare the recent compositions of municipal solid waste in the UK and USA.

13.15 In the UK there is about 28 million tonnes of domestic waste each year. If the distribution of the contents is the same as in Table 13.5 and the energy efficiency of collection is 50%, how much energy in kWh is available?

13.16 The estimated energy cost of waste collection is about 5000 MJ/tonne. What is the overall annual energy cost in kWh of collecting 28 Mtonnes/year of domestic waste?

13.17 Why is the hydrogen-powered fuel cell such an attractive option as a future energy source?

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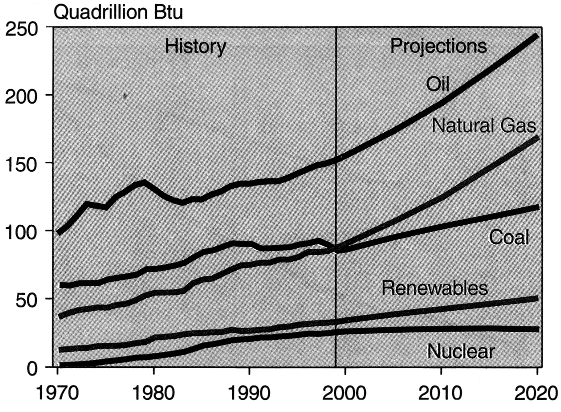
CHAPTER 14

THE ENERGY FUTURE

14.1. The Energy Problems

All the indicators and projections suggest that there will be increased world use and demand for energy into the forseeable future, Fig. 14.1. Energy demand is likely to grow faster than the increase of world population, Fig. 2.9 of Chapter 2, due to increased industrialisation and higher living standards. Moreover, the rate of energy demand is rising fastest in the developing countries of the non-OECD grouping. The US Department of Energy projection, Fig. 14.1, shows that the use of fossil fuels and of renewable sources is expected to increase for another 20 years. Only the use of nuclear power is projected to remain fairly steady.

A projection from a separate source, within the petroleum industry, is shown in Fig. 14.2 [2]. There is expected to be a reduction of oil and coal usage. Most



Sources: **History:** Energy Information Administration (EIA), Office of Energy Markets and End Use, International Statistics Database and *International Energy Annual 1999*, DOE/EIA-0219(99) (Washington, DC, January 2001). **Projections:** EIA, World Energy Projection System (2001).

Fig. 14.1. World energy consumption, by fuel type, 1970–2020 [1].

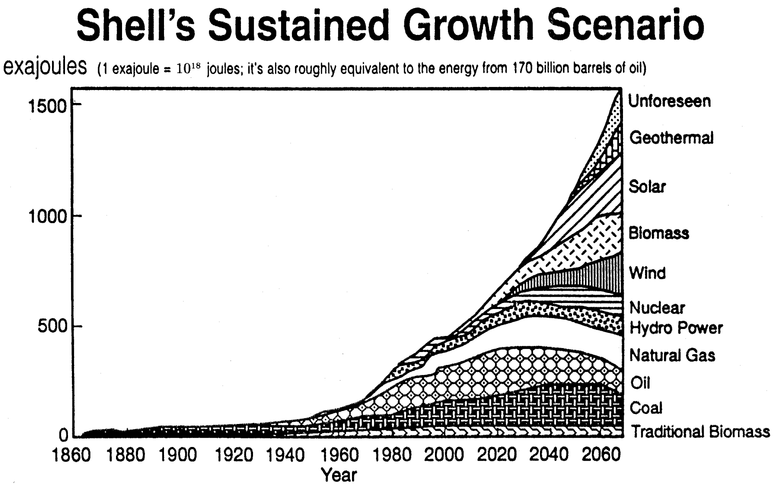


Fig. 14.2. Energy growth scenario (courtesy of Shell International).

significantly, the forecast indicates increased use of nuclear and renewable sources from the turn of the century onwards. This particular scenario also predicts that carbon emissions from the use of fossil fuels will peak in about 100 years, stabilising the atmospheric carbon dioxide at about 60% above present levels with significant climatic effects.

The many uncertainties make it impossible to accurately predict detailed forward demand for energy. But if there is no further major dislocation due to, for example, large-scale and lengthy global wars, the main energy issues discussed in Sec. 2.7 of Chapter 2 will arise. These are repeated here.

Problem 1

A need for a continuing source of gasoline and diesel fuels for motor vehicles and aircraft.

Problem 2

A need for a continuing supply of prime fuel for use in the generation of electricity (on the assumption that oil and natural gas will ultimately be unavailable in large supply).

14.2. An Energy Strategy

Problem 1, concerning oil supply, can be addressed in terms of:

- new oilfield discoveries
- enhanced recovery rates of natural crude oil
- the development of an economic synthetic fuels industry, such as tar sands

- major social adjustments in the pattern of private motoring
- some alternative form of road transportation (such as the electric car)
- further development of mass transportation systems using electricity-powered rail vehicles

Problem 2, concerning electricity generation, can be addressed simultaneously on both the short-term and long-term levels.

In the short term:

- use of coal and coal products
- reinstatement and increased use of nuclear fission power, using breeder reactors

In the longer term, the future seems to lie with renewable energy sources:

- solar energy
    - photovoltaic conversion
    - solar-thermal systems
    - wind turbine systems
    - ocean thermal currents
    - water wave energy
    - hydro-power
    - biomass and photosynthesis
- geothermal energy
- gravitational energy
    - tidal energy
- thermonuclear fusion

14.3. The Long-Term Energy Future

There appear to be four sources of energy that are adequate to sustain a greatly increased world population. The energy sources need to supply heat and electrical energy to homes, commercial premises and manufacturing industry, to fuel transportation services and to contribute to food production.

Use of the term "alternative energy" should be avoided on the grounds that, ultimately, there will not be alternatives [3]. Also, rather than use of the term "renewable energy" it might be better to classify the ultimate sources below as "indefinitely sustainable energy sources". Each of the four energy sources listed below could supply up to ten times our present energy requirements and for thousands of years.

Nuclear fission, using breeder reactors
Solar energy, of various forms
Controlled thermonuclear fusion
Geothermal energy

These four energy forms differ widely in their readiness for use, in their likely side effects, and in their economics. Moreover, present knowledge is not sufficient to make meaningful economic comparisons and permits only limited comparisons in respect of environmental and safety risks or of the likelihood of successful technical development. In engineering design the risks involved in compromises between safety and economics often cannot be fully seen until full-scale operation is realised and operational experience is gained [4].

It would be wise to continue research and development in all four of the areas listed above, even though the investment required is massive. Choices and priorities should not be made at this stage. A combination of long-term options is more flexible and more reliable than dependence on a single option.

14.3.1. *Nuclear fission using breeder reactors*

Since uranium, like the fossil fuels, is finite and non-renewable, the long-term future of nuclear fission as an electricity generation source depends on the use of breeder reactors, discussed in Sec. 8.5.4 of Chapter 8. The liquid-metal fast breeder reactor is the choice of those countries operating or planning to operate fast breeder reactor (FBR) stations, namely France, Germany, Japan, Russia and the UK.

Early enthusiasm for FBR programmes, in the 1970s and 1980s, has significantly waned. Of the 430 nuclear reactors operating worldwide in 1993, only 4 were breeder systems — one in Russia, two in France and one in the UK. A further FBR system started in Japan in 1995, rated at 246 $\mathrm{MW_e}$. At present (2002), the total world capacity of the breeder stations is 2473 $\mathrm{MW_e}$ out of a total world nuclear capacity of 351,746 $\mathrm{MW_e}$, which is 0.70% [5].

The loss of public confidence in the nuclear industry that has arisen in the last ten years in Britain and the USA has greatly inhibited the funding and development of breeder reactors. In particular, the USA, which is energy-rich and a world leader in so many fields of endeavour, has no FBR programme in operation or planned.

14.3.2. *Solar energy*

Solar energy is, in several ways, the most appealing option to provide an indefinitely sustainable energy source. The risks associated with solar heating are small and public confidence is high. Controversies that arise in the proposed development of nuclear energy, and even wind energy, are avoided.

At present certain solar heating applications are economical. Domestic space heating, domestic hot water heating, the industrial production of hot water or low-pressure steam and some agricultural heating applications are well developed.

Photovoltaic arrays for the direct production of electricity are an established technology of high appeal but, at present, high cost. Fundamental research could yield dramatic returns and progress to date is encouraging.

In the UK the form of solar energy that is likely to be the most economically viable is the use of large wind turbines. The amount of land per unit of electrical capacity is larger than for other forms of solar energy [4]. Also, there are environmental objections to land-based wind farms such that the use of offshore sites is now (2002) established and is moving forwards.

A long-term potential option is to use solar energy for the production of fluid fuels by direct photochemical conversion. For example, the decomposition of water can be used to produce hydrogen. This could be used directly as a fuel or in the synthesis of hydrocarbon fuels. It is possible to realise photochemical conversion efficiencies of 20–30%, based on incident solar energy, compared with an average photosynthetic efficiency of 0.1% for natural ecosystems and up to 1% for intensive biomass systems [4].

14.3.3. *Controlled thermonuclear fusion*

Despite the enormous sums spent on research all over the world, large-scale nuclear fusion has yet to be demonstrated as technically feasible. The successful development of fusion-derived energy would solve mankind's energy problems permanently. Radioactivity produced in fusion devices could be from ten to several hundred times smaller than from fission reactors. The problems associated with commercial traffic in weapons-usable fissile materials are largely absent [4]. Compared with the use of fast breeder fission reactors, the fusion option has fewer environmental, proliferation or safety problems. Moreover, its raw material source base is very large.

Thermonuclear fusion will be (hopefully) part of tomorrow's technology. It represents so immense a potential that the momentum of international research must be maintained, even though progress is slow. If and when the basic scientific problem of controlled and sustained fusion is realised, there may need to follow something like 20 years of engineering development.

14.3.4. *Geothermal energy* [4]

At present the only usable geothermal sources are deposits of hot water or natural steam. In the long-term future it may be possible to extract heat from the natural thermal gradient in the earth's crust and from unusually hot rock formations lying close to the surface. The possible use of hot dry rock as a heat source depends on developing a fracture system large enough to be economical. The technical and environmental implications of this are speculative.

A potentially large source of low-temperature geothermal energy is geopressurised brines, for example those off the Mexican Gulf coast. If the heat and dissolved natural gas can be exploited simultaneously this could become a major energy source. Such exploitation is still speculative and the technical implications are not fully known.

14.4. What Shall We Do When the Oil Runs Out?

In the absence of the fossil fuels there remain only four sources that can provide energy on the scale demanded by present, and projected future, populations. These are listed in the preceding section and are repeated here:

Nuclear breeder reactors
Solar energy
Thermonuclear fusion reactors
Geothermal energy

The last two options are not likely to be available on the required scale for 20–25 years, and perhaps longer.

There seems to be a strong case for a big upsurge of investment in both solar and nuclear fission systems [6]. The political misgivings in Britain and the USA about nuclear electric power should be reconsidered [7]. Smaller contributions such as energy efficiency [8], reduction of wastes, use of biomass, hydroelectric schemes, tidal barrages, etc. are important and welcome, but they will not close the energy gap.

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ANSWERS

Chapter 1

1.1. Use Eq. (1.6).

1.2. (a) PE $= 100 \times 9.81 \times 25 = 24525$ J
 (b) PE $= 0$, KE $= 0$
 (c) $mgh = mgh/2 + 1/2\ \mathrm{mv}^2$
 $v = \sqrt{gh} = 15.66$ m
 (d) PE $= 12262$ J, KE $= 12262$ J

1.3. (a) $a = 100/100 = 1\ \mathrm{m/s^2}$
 (b) KE $= 1/2\ \mathrm{mv}^2 = 1/2\ (100)\ (100) = 5000$ J
 Momentum $=$ mv $= (100)\ (10) = 1000$ kg/s

1.4. $v = \omega r = 10 \times 0.5 = 5$ m/s
 $T = Fr = 10 \times 0.5 = 5$ Nm
 $\alpha = T/mr^2 = 5/(1 \times 0.5^2) = 5/0.25 = 20\ \mathrm{rad/s^2}$

1.5. $J = mr^2 = 1 \times (0.5)^2 = 0.25\ \mathrm{kg^2}$

1.6. $W_{\mathrm{KE}} = 1/2J\omega^2 = 1/2 \times 1 \times 0.5^2 \times 10^2 = 12.5$ J

1.7. 1800 rpm $\equiv 6\pi$ rad/s
 KE $= 1/2mr^2\omega^2 = 1/2 \times 10 \times 1^2 \times (6\pi)^2 = 1776$ J

1.8. 1 UK gallon $= 4.55$ litres $= 4500\ \mathrm{cm^3} = 4.55$ kg
 $Q = 4550 \times 1 \times 20 = 91000$ cal
 $W = 4.2 \times 91000 = 382.2$ kJ

1.9. (a) Final temperature $T_{\mathrm{f}} =$ initial temperature T_{in}
 (b) From the formula in Example 1.4 the mass and specific heat terms cancel out:

$$T_{\mathrm{f}} = \frac{T_{\mathrm{in}} + 2T_{\mathrm{in}}}{2} = \frac{3}{2}T_{\mathrm{in}}$$

1.10. 10°C = 283 K, 100°C = 373 K
 $\eta_{\mathrm{Carn}} = 1 - 283/373 = 1 - 0.759 \equiv 24.1\%$

1.11. (a) $\eta_{\text{Carn}} = 1 - 300/900 = 1 - 0.333 = 0.667$
$\eta_{\text{working}} = 0.667/2 = 0.333$
(b) $W = 0.333 \times 500 = 166.5$ MJ
1.12. $\eta_1 = 1 - 373/673 = 0.45$, $W_1 = 0.45Q$
$\eta_2 = 1 - 373/473 = 0.211$, $W_2 = 2 \times 0.211Q = 0.422Q$
Better to use a single source.
1.13. 35°F = 1.67°C = 274.8 K
68°F = 20°C = 293 K
$\eta_{\text{Carn}} = 1 - 274.67/293 = 1 - 0.937 = 6.3\%$
$\eta_{\text{pract}} = 0.65 \times 6.3\% = 4.1\%$
1.14. (a) $Q_{\text{H}} = 11.194$ MBTU, $Q_{\text{L}} = 5.933$ MBTU, $W = 5.261$ MBTU,
$Q_{\text{H}} - Q_{\text{L}} = W$
(b) $\eta_{\text{turbine}} = 5.261/11.194 = 47\%$
(c) It is necessary to determine the energy content of 1000 pounds of solid fuel and deduct 12.72 MBTU
(d) $\eta_{\text{gen}} = 5.209/5.261 = 99\%$
1.15. $T_{\text{L}} = 10°\text{C} = 283$ K
initially $0.38 = 1 - 283/T_{\text{H}}$ or $T_{\text{H}} = 456.5$ K
finally $0.5 = 1 - 283/T_{\text{H}}$ or $T_{\text{H}} = 566$ K

$$\text{Temperature rise} = 566 - 456.5 = 109.5°\text{C}$$

1.16. The refrigerator mechanism tries to refrigerate the room. It works continuously at full load drawing its maximum input power.
1.17. $T_{\text{H}} = 873$ K
(a) $0.3 = 1 - T_{\text{L}}/873$ so that $T_{\text{L}} = 611$ K
(b) From (1.33), $0.3 = 1 - Q_{\text{L}}/1000$, giving $Q_{\text{L}} = 700$ MJ
From (1.31), $\Delta S = 700/611 - 1000/873 = 1.1457 - 1.1455$
$= +0.0002$ J/K
1.18. (a) 100°C, (b) 37.8°C, (c) 0°C, (d) −17.8°C
1.19. (a) 413.6°F, (b) 212°F, (c) 89.6°F, (d) 32°F
1.20. −40°C = −40°F
1.21. 24.33°C
1.22. 67.2°F
1.23. (a) $(2 \times 10^9)/746 = 2.68 \times 10^6$ HP, (b) 2000 MJ/s, (c) 2×10^6 kW,
(d) 1474×10^6 ft lb/s
1.24. $50/3.6 = 13.9$ kWh
1.25. $(3 \times 10^6)/747 = 4021.5$ HP

Chapter 2

2.1. 1.256×10^{14} m^2
2.2. 6.36×10^6 m or 3961 miles

2.3. Two different interpretations possible:
(i) if the radiation intercepted is 1.73×10^{17} W (Sec. 2.1.1), then

$$\begin{aligned}\text{fraction} &= \frac{1.73 \times 10^{17} \times \text{number of seconds in 24 hours}}{3 \times 10^{32}}\\ &= 5 \times 10^{-11}\end{aligned}$$

(ii)

$$\begin{aligned}\text{earth interception} &= \frac{\text{earth interception area}}{\text{sun radiation area at earth distance}}\\ &= 4.48 \times 10^{-10}\end{aligned}$$

Why are the two values in (i) and (ii) different?

2.4. 1.733×10^{17} J/s

2.5. (i) 47%, (ii) 0.21%, (iii) 23%, (iv) 0.0023%

2.6. The Industrial Revolution in England. Mass migration of population from country to towns. Building of factories. Invention and use of steam engines.

2.7. (a) 40 years (b) 10 years (c) 20 years
2.8. (a) 60 years (b) 12 years (c) 80 years
2.9. (a) 220 years (b) 215 years (c) 660 years
} precise reading of Fig. 2.3 is not feasible

2.10. Small population (4.46 M), abundant hydroelectric power and 50% stake in the North Sea oil and gas fields — by implication, a massive fuel exporter.

2.11. To move towards higher GNP/capita.
To move towards lower energy/capita.

2.12. They perceive that economic success is based on industrial development (not on agriculture). But this is energy-intensive and requires a vast capital endowment of funding (Japan was rebuilt after World War II by American money).

2.13. Australia, Canada and New Zealand have small populations in large areas of agricultural land.

2.14. Large country with mobile population. Much air travel. Traditional users of large size motor vehicles. A tradition of cheap gasoline. Major fuel deposits of coal, gas and oil. Higher level of general prosperity. Labour-saving (i.e. energy-burning) homes.

2.15. See answer to 2.12.
There are no available sources of foreign capital to increase their rate of industrialisation. Further demands on fossil fuel sources would reduce the world reserves at an increased rate, assuming that they could afford to buy the fuel. The possibility that some countries might take military action against others to appropriate their oil.

2.16. Since 1973, in the UK, certain important changes have occurred.

(i) The coal industry has steadily declined. Production (Table 2.6) in 2000 reduced to 19.5/82.6 or 23.6% while consumption (Table 2.5) reduced to 37.7/83.2 or 45.3% of the 1973 figures. In 1973, coal production and consumption were in balance. In 2000, (37.7–19.5)/37.7 or 48.3% of the coal consumed was imported.

(ii) In 1973, virtually all of the oil consumed was imported. By 2000, the primary consumption had levelled out at almost 75% of the 1973 figure, all home-produced. In addition to self-sufficiency, almost 40% of the oil production was exported.

(iii) In 1973, the UK production and consumption of natural gas was almost in balance. Consumption then exceeded production for about 20 years, necessitating imports.

Since the early 1990s production has exceeded consumption, providing exports. In 2000, (97.3–86.1)/97.3 or 11.5% of the production was (by implication) exported.

2.17. Is there a need for an energy policy addressing all aspects of the problem? Should the UK government be producing firm guidelines for future action? Is it an issue that should be left to the oil companies?

2.18. From Fig. 2.14: Sweden and Iceland. (What are the sources of their non-fossil energy?)

2.19. Should the installation of catalytic converters on automobiles be mandatory? Should there be legislation to limit the numbers of automobiles? Should vehicle taxation levels be adjusted to favour low carbon dioxide emitter level vehicles?

2.20. The big emission producers are the energy industry and big manufacturers. Further taxation would reduce profits and possibly result in job losses. Is this an acceptable situation?

2.21. The authors see no way in which the Kyoto Protocol can be levied other than by voluntary action.

2.22.

Largest emissions:	Largest per capita emissions:
USA	Australia
Russian Federation	Luxembourg
Japan	Canada
Germany	New Zealand
Ukraine	Ukraine
Canada	Denmark

2.23. Small populations generating little carbon dioxide. Large agricultural sector with the use of nitrogenous fertilisers.

2.24. Very energy-conscious. Widespread use of nuclear-powered electricity. No oil industry.

Chapter 3

3.1. 0.2 A, 40 W

3.2. 20 ohms, 2880 W

3.3. 24 ohms, 0.3125

3.4. $P_{\text{out}} = 2 \times 746 = 1492$ W
$P_{\text{in}} = 200 \times 10 = 2000$ W
$\eta = 74.6\%$

3.5. 74.6%, 0.805

3.6. The input power is unchanged.
$I = P/V = 2000/120 = 16.67$ A

3.7. With balanced sinusoidal currents it is possible to supply three separate phase circuits using only three conductors. (Whereas six conductors would be needed with three single-phase generators.) The saving on copper wire and transmission system construction costs is very large.

3.8. High voltage permits low current and smaller size transmission line conductors.

3.9. See Sec. 3.4.

3.10. From Table 3.1, by implication it is the USA.

3.11. From Fig. 3.6; Canada, USA, Western Europe, Eastern Europe/former Soviet Union. Intensive energy use and a small population.
Severe winter climate.

3.12. From Table 3.2, taking the ratio 2020 figure/1996 figure gives

oil = 19.6/13.3 = 1.47
coal = 78.3/52.8 = 1.48
renewables = 49.7/30.7 = 1.62
natgas = 57.7/22.5 = 2.56
nuclear = 21.7/24.1 = 0.9
total = 227/143.4 = 1.58

There is projected to be a large increase in the proportion of natural gas and a reduction of nuclear power.

3.13.

Fuel	1980	2000
coal	71.7%	31%
oil	12.7%	1.38%
natgas	0.6%	38.9%
nuclear	12.2%	21.2%
hydro + renewables	2.75%	1.38%

Note: why don't the totals add to 100%? (See Table 3.3.)

3.14. Estimating from Fig. 3.10:

Fuel	1996	2020
coal	50%	52%
oil	2%	< 1%
natgas	8.5%	21%
nuclear	20%	8.5%
renewables	21%	19%

The trends are a much increased use of natural gas and reduction of the use of nuclear power. Note that the figures do not add up to 100% because of the difficulty of reading the bar chart accurately.

3.15. From Table 3.3, 14.2% was imported in 2000. This was imported from France via the undersea cable link.

3.16. See Tables 3.3 and 3.5
   (a) in 1998, $8836/355200 = 2.49\%$
   (b) in 2000, $23295/369300 = 6.31\%$

3.17. See Sec. 3.8.2; in 2001, 8% of US electricity was generated from CHP schemes.

3.18. see Sec. 3.8 and Fig. 3.11; the efficiency improvement was from about 35% to 70%.

3.19. More expensive first cost. Motor operates below its rated load, with reduced efficiency.

3.20. Its light appears to be yellow in colour and casts people in an unflattering aspect — they look pale and peculiar.

3.21. Lamps operate for $8 \times 5 \times 40 = 1600$ hours/year.
   (a) $20 \times 100 \times 8 \times 5 \times 40 = 3200$ kWh
   $3200 \times 0.07 =$ £224
   (b) Lamp replacement time $= 1000/1600 = 0.625$/year
   Annual labour cost $= 20 \times 5/0.625 =$ £160
   Lamp replacement cost $= 20 \times 0.5/0.625 =$ £16
   (c) Annual cost = £224 + £160 + £16 = £400

3.22. Lamps operate for 1600 hours/year as in (3.21).
   (a) Annual consumption $= 30 \times 70 \times 1600 = 3360$ kWh
   Annual cost $= 3360 \times 0.70 =$ £235.2
   (b) Lamp replacement times $= 10{,}000/1600 = 6.25$ years
   Annual labour cost $= 30 \times 5/6.25 =$ £24
   Tube replacement cost $= 30 \times 4/6.25 =$ £19.2
   (c) Total annual electricity costs = £235.2 + £24 + £19.2 = £278.4

3.23. (a) Annual cost saving = £400 − £278.4 = £121.6
   (b) Payback period $= 660/121.6 = 5.43$ years
   (c) Levels of illumination/unit area

incandescent	fluorescent
$20 \times 100 \times 12/150$	$30 \times 70 \times 64/150$
$= 1600\ \ell\text{m}/\text{m}^2$	$= 896\ \ell\text{m}/\text{m}^2$

Although the fluorescent option represents an energy saving, the reduction of illuminance could be a serious disadvantage. The Illuminating Energy Society of North America recommended lighting level for classrooms/lecture rooms is category F, which is 1000–2000 lux (lumens/m^2) [16].

Chapter 4

4.1.

Coal Producers (2000 mtoes)		Coal Consumers (2000 mtoes)	
USA	570.7	USA	564.1
China	498	China	480.1
Australia	155.6	India	163.4
India	154.3	Russian Fed.	110.4
South Africa	118.8	Japan	98.9
Russian Fed.	115.8	Germany	82.8
Poland	68.1	South Africa	81.9
Germany	56.4	Poland	57.1
Indonesia	47.3	Australia	46.7
Ukraine	42.1	South Korea	42.9

4.2. Big importers: Japan, South Korea, Germany, UK, France
Big exporters: Australia, USA, South Africa, Indonesia

4.3. (a) Increases: USA, Australia, Indonesia
(b) Decreases: China, Germany, Hungary

4.4. (a) Increases: USA, India, South Korea
(b) Decreases: China, UK, Poland, Germany

4.5. In the UK coal production reduced by (130.1–37.1)/130.1 or 67.8% of the 1980 figure. Coal consumption reduced by (123.5–55.9)/123.5 or 54.7% of the 1980 figure.

4.6. In the USA coal production increased by 8.8% but coal consumption increased by 12.2% in the period 1989–1999. Production still exceeds consumption, making the USA a coal exporter.

4.7. From Table 4.7, in the period 1970–2000, UK deep mined coal production fell by $\frac{136.7-17.2}{136.7} = 87.4\%$ of the 1970 figure, while the opencast (surface) mined coal production increased by $\frac{13.4-7.9}{13.4} = 41\%$. The proportion $\frac{\text{opencast}}{\text{deep mined}}$ rose from $\frac{7.9}{136.7} = 5.8\%$ to $\frac{13.4}{17.2} = 78\%$ in 2000.

4.8. The UK domestic sector accounted for $\frac{1.9}{59} = 3.22\%$ of the total consumption in 2000, compared with $\frac{20.2}{156.9} = 12.9\%$ in 1970. The reduction represents the UK preference for gas-fired domestic heating. (Table 4.8)

4.9. Between 1980 and 2000, the proportion of coal changed from $\frac{89.6}{123.5} = 72.5\%$ in 1980 to $\frac{46.1}{59} = 78.1\%$ in 2000. (Table 4.8)

4.10. European coal has to be deep mined, whereas US coal is surface mined and the cost/ton of extraction is cheaper.

4.11. Mostly as fuel for electricity generation.

4.12. (a) Cheap, readily available, easily transportable
    (b) Dirty, unhealthy, inefficient fire grate systems, smoke pollution
4.13. (a) Cheap, readily available, easily transportable
    (b) Pollutant gases and particulates, creation of solid ash, acid precipitation, greenhouse gases
4.14. Mainly by rail, but by waterway if feasible.
4.15. See Sec. 4.3.2.
4.16. Sulphur oxides, nitrogen oxides, carbon monoxide, carbon dioxide, particulates
4.17. See Sec. 4.4.2.3.
4.18. Ionisation of solid carbon particles by passing them through an electric field.
4.19. See Sec. 4.6.
4.20. The low and stable price of oil has undercut all other options, including coal.

Chapter 5

5.1. The oil producer countries OPEC realised that they had the power to fix their own oil prices and not be dependent on western oil companies.

5.2.

Consumption (mto)		Production (mto)	
USA	897.4	Saudi Arabia	441.2
Japan	253.5	USA	353.5
China	226.9	Russian Fed.	323.3
Germany	129.5	Iran	186.6
Russian Fed.	123.5	Mexico	172.1
South Korea	101.8	Venezuela	166.8
India	97.6	China	157.5
France	95.1	Norway	157.5
Italy	93	Iraq	128.1
Brazil	84.4	Canada	126.3

5.3. Increasing industrialisation of China, Japan and the Pacific Rim countries.
5.4. Use Table 5.4 to compile data on 2000 consumption minus 1990 consumption and divide by 11 for the average increase/year. The winners (losers?) are China and the USA.
5.5. Use Table 5.3 to calculate the 2000 production minus the 1990 production and divide by 11. In numerical order the result is Norway, Saudi Arabia, Kuwait and Venezuela.

5.6. The Sultan of Brunei owns all of Brunei's oil (9.5 million tonnes in 2000).

5.7. Atlantic Ocean, into USA; Indian and Pacific Oceans, to the Far Fast.

5.8. (a) The output of Iran, the Gulf States and Saudi Arabia totalling roughly one quarter of world oil production in 2000.

(b) Large-scale curtailment of industrial production in Western Europe and Japan.

Severe restrictions in North America for any period of closure.

5.9. $\frac{897.4-353.5}{200\times 10^3} \times 10^6 = 2719$ tankers

5.10. See Table 5.6.

5.11. See Table 5.6.

5.12. See Table 5.6.

In 1970, the UK made a loss of 0.5 billion pounds sterling.

In 2000, the UK made a profit of 6.6 billion pounds sterling.

5.13. From Fig. 5.7, Venezuela and Saudi Arabia.

5.14. In 1995, consumption 807.7 mto, production 384 mto, deficit $= 807.7 - 384 =$ 423.7 mto.

5.15. Large country with widespread population. Long car journeys are routine. Large internal air services greatly used. Car ownership universal, from teenage onwards. Historical tradition of cheap gasoline. High levels of affluence. Labour-saving (i.e. energy-using) homes.

5.16. Fuel prices and fuel tax levies are a political "hot potato". In the UK in 2000, farmers and self-employed transport workers, enraged by yet another fuel tax increase, blockaded fuel depots, causing a considerable crisis. Within three days fuel pumps were dry. Within five days supermarket shelves were becoming empty and reports of theft of fuel and groceries were rife. The government's opinion poll rating dropped like a stone as everyday life became seriously disrupted within just one week.

Despite the relatively tiny tax levy on US fuel, sharp increases in gas pump prices in 1999 caused threats of industrial action and an expedient partial climb-down by federal authorities.

The extremely sensitive link between public opinion and fuel prices gives sobering food for thought about the consequences which could ultimately occur if the world supply of oil brought about shortages and/or large price increases. A future "oil war" is not at all beyond the realm of possibility — indeed, a regional oil war (the UN–Iraq war over Kuwait) has already taken place.

If the shortages were not sudden, but a gradual squeeze on supply forced prices very high, diplomatic pressure to increase supply would be exerted on the producer countries, which rely heavily on global markets for prosperity. Secondly, consumer countries would move to utilise more of their less economically viable resources (e.g. coal, shale oil) to buffer the shortfall.

5.17. The reassessment of reserves has gone upwards. Certain new oilfield discoveries.

5.18. Recognition of the problem. Addressing of the problem at government and international level. An assessment of overall energy use and supply.

5.19. Move out of oil and natural gas into renewables or nuclear or coal or some combination.

5.20. Without the military and economic leadership of the USA there could be oil anarchy. A possibility of major wars to possess and control the world oil supply.

5.21. Deep mining. Large amounts of rock waste for surface disposal. Large requirement of processing water that becomes contaminated. Gas or dust emissions. Despoliation of mining sites. Very expensive compared with imported crude oil.

5.22. The oil companies are immensely rich and realise the value of good public relations. Everybody needs oil for transportation. The need for coal to generate electricity (universally sought) is less well perceived. Carbon dioxide emissions are mostly invisible. Power station effluent is highly visible. Coal burning results in acid rain.

Chapter 6

6.1.

Producers (mtoe)		Consumers (mtoe)	
USA	500	USA	588.9
Russian Fed.	490.5	Russian Fed.	339.5
Canada	151	UK	86.1
UK	97.3	Germany	71.3
Algeria	80.4	Canada	70.1
Indonesia	57.5	Japan	68.6
Kuwait	54.2	Ukraine	61.06
Netherlands	51.6	Iran	56.6
Norway	47.2	Uzbekistan	44.8
Uzbekistan	47	Saudi Arabia	42.3

6.2. Political breakup of the former Soviet Union. Abandonment of central control (from Moscow). Autonomous decision making by the countries of the former Eastern bloc.

6.3. In the period 1990–2000, the consumption of natural gas doubled in Algeria, Argentina, China, India, Iran, Malaysia, Norway and the UK. It increased of the order 50% in Pakistan, Saudi Arabia and Uzbekistan.

6.4. From Fig. 6.7 the trade routes are (i) Eastern Europe to Western Europe, (ii) Canada to the USA, (iii) SE Asia to Japan, (iv) North Africa (Algeria) to Europe.

6.5. In the UK natural gas production has exceeded consumption since 1995, Fig. 6.9.

6.6. In the USA consumption has exceeded production in all the years since 1984, Fig. 6.12.

6.7. From 1990 ⟶ 2000, the average annual increase of consumption was $\frac{86.1-47.2}{11} = 3.54$ mtoe/yr.

6.8. $\frac{588.9-486.3}{11} = 9.33$ mtoe/yr.

6.9. From Table 6.3, the 2000 consumption of natural gas from North America (31.9%), Europe (19.1%), Australia (0.9%) and New Zealand (0.2%) added up to 52.1% of the world total.

6.10. From Table 6.1, in 2000:

(a) North America 4.9%
(b) Europe 3.5%
(c) FSU 37.8%
(d) Middle East 35%
(e) Africa 7.4%
(f) Asia-Pacific 6.8%.

6.11. New discoveries, revised estimates of reserves and improved extraction rates.

6.12. Most likely by producing liquid natural gas (LNG) and using refrigerator ships.

6.13. The alternative, using long pipelines, is too uncertain for political reasons. Known deposits of coal.

6.14.

low BTU	3–6 MJ/m
medium BTU	10–22 MJ/m
high BTU	37 MJ/m

6.15. Natural gas is cheap, safe and more efficient than coal.

6.16. Natural gas and coalbed methane consist mainly of methane, obtained directly in the gaseous state. Coal gas has to be manufactured by the burning of coal.

6.17. The low cost of oil has made the other options expensive and (apparently) unnecessary.

Chapter 7

7.1. Sec. 7.3.

7.2. Due to high pressure.

7.3. In the seismic areas described in Fig. 7.3.

7.4. Cotopaxi — Brazil
Fujiyama — Japan
Hekla — Iceland
Katmai — Alaska
Kilauea — Hawaii
Krakatoa — Indonesia
Lassenpeak — USA
Semeru — Indonesia
Mauna Loa — Hawaii
Mount Etna — Italy
Mount St. Helens — USA
Ngauruhoe — New Zealand
Osorno — Chile
Paricutin — Mexico
Popocatepetl — Mexico
Stromboli — Italy

Reference to Fig. 7.3 shows that they are all in seismic regions.

7.5. Geothermally heated greenhouses.
7.6. Larderello — Italy
The Geysers — west coast of USA
Otake — Japan
Matsukawa — Japan
Wairakei — New Zealand
Stromboli — Italy
Pauzhetsk — eastern Russia
Cerro Prieto — Mexico
Niland — USA
Ahuachapan — Central America
Hveragerdhi — Iceland
Reykjanes — Iceland
Namafjall — Iceland
7.7. The aquifers are too low in temperature and of inadequate flow rate.
7.8. Dry steam, wet steam, hot brine, dry rocks, molten magma.
7.9. Necessity to fracture the rock underground in a controlled manner.
7.10. See Fig. 7.6.
7.11. Geothermal energy is largely unused. The risks and problems of exploration are similar to those involved in oil exploration. Environmental problems might include [2]: land use, noise and damage during drilling, visual impact of power and heat extraction plant, need for suitable heat distribution system, release of gases, liquids and chemicals, physical effects of the local area geological structure.
7.12. Uneconomical due to low flow rate and lower-than-expected temperature.
7.13. See Table 7.3.
UK does not lie in a seismic zone.
7.14. 1295 tonnes

Chapter 8

8.1. 2667 tons of coal
8.2. (i) 3.2×10^{-11} J, (ii) 8.91×10^{-18} kWh
8.3. 0.33 ton ore (compared with 1.8 ton without enrichment; see Example 8.2).
8.4. From (8.10),
(i) $3.32\ T_{1/2}$, (ii) $6.64\ T_{1/2}$
8.5. See Sec. 8.3.1.
8.6. 2337 million years
8.7. $\lambda = 0.639/30 = 0.0231$
8.8. From (8.9), $T_{1/2} = 0.693/0.131 = 5.29$ years
8.9. 10 years
8.10. 1 rad dose = 1 rem
1 mrem = 1/1000 rem

100 rems = 1 sievert
100 rads = 1 gray

8.11. W = 1 joule/kg = 1 gray at 100 rads dose
For a person weighing 150 lb (150 × 2.2 = 330 kg) the whole body radiation energy input is 330 J or 330 watt seconds.

8.12. See Sec. 8.4.3.1; 200 mrem/year

8.13. See Sec. 8.4.3.2;
0.3 mrem/year from the nuclear industry
500 mrems/year from all sources

8.14. See Sec. 8.5.1.

8.15. Business is not convinced of the commercial viability, especially with regard to decommissioning costs. The public is not convinced regarding the safety of nuclear reactor operation.

8.16. The natural uranium supply is being depleted and is not renewable. Breeder reactors simultaneously generate heat and breed plutonium, using smaller reactor core sizes.

8.17. See answer to 8.15.

8.18. See Sec. 8.6.

8.19. See Secs. 8.2.1 and 8.8.1.

8.20. See Sec. 8.8.1.

8.21. (i) 35.84×10^{-13} J, (ii) 9.98×10^{-19} kWh

8.22. Deuterium and lithium are cheap, abundant and non-radioactive materials.

8.23. No — it is a complex, multifaceted situation. Nuclear fission is a mature industry that is making great contributions to electricity generation worldwide but is in decline in the USA, which is the richest, most powerful and most influential country in world energy. Nuclear fusion is still at the scientific experiment stage. If it works on a commercial scale, which is probable but not certain, such a development is at least 20 years hence.

8.24.

Advantages	Disadvantages
Cheap, abundant, non-fossil fuel.	Still experimental and far from maturity.
Level of associated radioactivity much lower than for nuclear fission.	Requires major advances in several scientific areas.
International collaboration (not competition as with nuclear weapons).	Requires massive investment in an unproven technology.
Another energy option.	Still a generation of time from realisation.
Does not create any "greenhouse" gases.	Other options are starting to look more attractive.

8.25. See Sec. 8.8.2(c).

Chapter 9

9.1. Values in mtoe:

Canada 30.8	China 19
Brazil 26.2	Russian Fed. 14.2
USA 23.4	Norway 12.2

9.2. (a) China, Brazil
(b) There are no overall significant decreases.

9.3. In the year 2000, 230.4/8752.4 = 2.63% of the world total primary energy consumption was due to hydroelectricity.

9.4. 74.6 m^3/s

9.5. See Sec. 9.1.1.

9.6. 424.7 m

9.7. (a) Axial-flow (propeller) turbine (e.g. Kaplan)
(b) Reaction turbine (e.g. Francis)
(c) Impulse turbine (e.g. Pelton)

9.8. 365.2 m^3/s
6.47×10^6 tons

9.9. (v) Not all rain is available as surface run-off.
Not all run-off appears in streams that are worth damming.
If run-off descent is at too small a slope, piping difficulties limit the available head.
(vi) 10–30% in general

9.10. See Sec. 9.2.5.

9.11. From (9.20) with $h = 1$, $R = 6$

(a) $W = \frac{1}{2}\rho g A R^2[\frac{2}{6}]$; net gain is 33.33%.

(b) From (9.23), with $h = 1$, $R = 6$, $k = 0.8$ net gain is $0.333 - 0.007 \equiv$ 32.6%.

9.12. Use (9.22) and differentiate w.r.t. h/R.

9.13. 21.7%

9.14. 213 MW

9.15. Geometric solution, showing P is proportional to R^3.

9.16. 4491 MW

9.17. 0.1176 Hz, 112.8 m, 13.27 m/s

9.18. 74.8 kW/m
But the extractable power is likely to be about 30% of this.

9.19. $T = 9.47$ s, $P = 46.9$ kW/m

9.20. 20.1 kW/m

9.21. See Sec. 9.3.6.

9.22. Approx. 1660 m if wave converter is 30% efficient.

Chapter 10

10.1. Annual month-by-month wind variation in the UK — Fig. 10.5. Comparison with Fig. 3 shows (i) wind power monthly input matches the monthly demand for electricity, (ii) winter electricity demand is 2–3 times summer demand, (iii) winter wind energy flux density is 2–3 times the summer value.

10.2. Differentiate (10.12) w.r.t. (V_2/V_1) and equate the derivative to zero.

10.3. Since P αV^3 doubling V causes a $2^3 = 8$ times increase of P.

10.4. In Fig. 10.11, the vertical projection is about 40% of the distance from 10^4 to 10^5.
Estimate A = 30,000 m^2, D = 195 m.

10.5. See Sec. 10.5.3.
r = 90 ft = 27.43 m
V = 20 mph = 8.94 m/s
ω = 1.96 rad/s = 18.7 rpm

10.6. TSR = 7.61

10.7. (a) 0.26 – 0.45 per unit
(b) 0.084 – 0.26 per unit

10.8. If $\eta = 0.25$, $D = 4.45$ m.

10.9. If $\eta_g = 0.75$, $C_p = 0.35$ and there is no gearbox, $D = 12.12$ m.

10.10. $D = 3.65$ m (12 ft), when $\eta = 0.25$.

10.11. $V = 8.61$ m/s = 19.3 mph

10.12. Let the overall efficiency be 25%.

(a) $V = 6.26$ m/s = 14 mph
(b) TSR = 1.34
(c) $D = 3.54$ cm = 1.39 in

10.13. (a) $T = 3.54 \times 10^6$ Nm
$D = 68.4$ cm = 26.93 in
(b) See Sec. 10.5.2.
(c) TSR = 6.46
$D = 84.2$ m (276.3 ft)
(d) $\eta_g = 0.95$, $\eta_{gb} = 0.9$, $C_p = 0.351$

10.14. $d = 12$ in = 0.304 m
$T = 0.305 \times 10^6$ Nm

10.15. $N_{\max} = 35$ rpm
Propeller is feathered (turned into the wind) to limit rotational speed.
Excessive speed would cause large centrifugal forces on the blades plus possible bearing damage.

10.16. A vertical (horizontal axis) rotor acts as a rudder or stabiliser.

10.17. Supplementary starting required.
Use (a) Savonius rotor on same shaft, or (b) starter motor.

10.18. See Sec. 10.11.

10.19. See Sec. 10.2.1 and especially Fig. 10.5.

10.20. The middle section of the country, to the west of the great lakes. The windiest states are N. Dakota and S. Dakota. See Fig. 10.7.

10.21. The US Met. Office figures for Cleveland, Ohio show that this city has a mean annual windspeed of 10.9 mph (compared with 10.4 mph for Chicago) — Cleveland is about 10% windier than Chicago. In particular, Cleveland is windier in all the months from October through to April.

10.22. A speed of 100 rpm is much too small for a conventional design of electric generator. See Sec. 10.10.2 for some details.

The alternative is to use a gearbox or pulley system to step up the generator shaft speed.

10.23. See the data in Table 10.5.

See Sec. 10.10.2 for discussion about electric generator design.

10.24. See the data in Table 10.5.

10.25. The USA is the world's number one country in political, financial and military terms. It is also the biggest per capita consumer of energy and a massive importer of Middle Eastern oil. Since the Gulf War of 1992, the USA has become the military protector of Saudi Arabia, the world's biggest repository of oil. Americans have a tradition of cheap gasoline and wish to maintain it. The security of oil supplies and the price to consumers is a dominant issue in US domestic politics.

The economic feasibility of all other forms of energy has to be contrasted with the supply and price of oil in the USA.

10.26. (i) Air speed not affected

(ii) Ground speed is increased (America to Europe) or decreased (Europe to America) by 100 mph.

10.27. Air speed = 445 mph

Ground speed = 445 − 95 = 350 mph

Time = 3400/350 = 9.71 hours

Chapter 11

11.1. $\cos 9^\circ = 0.988$

11.2. From (11.1). Assume that the inclination of the collector compensates the altitude angle; then the radiation falls normally onto the collector: $G = 500 + 500 = 1000$ kWh/m^2.

11.3. $G = D(1 + \sin\alpha) = 320(1 + 0.636) = 523.5$ W

11.4. In (11.4), if $T_c \uparrow$, $(T_c - T_a) \uparrow$ and $\eta \downarrow$

11.5. Typical efficiency ≈ 40–50%. See Sec. 11.4.2.

11.6. Typical efficiency 30–40%. See Sec. 11.4.1.

11.7. See Fig. 11.16. Locate supplementary tank near to main tank for minimum pipe loss. System is working if supplementary tank is delivering water greater than cold tap temperature.

11.8. See Fig. 11.13. Depending on the working temperature, the use of double glazing could increase the thermal efficiency by up to 10% (Fig. 11.15).

11.9. See the latter part of Sec. 11.4.2.

11.10. Mass transferred in 5 hours = 360 kg.
Temperature rise = 11.68°C. Power = 773 W/m^2.

11.11. Heat collected in 6 hours = 28.12×10^6 joules.
Heat required to raise the tank temperature = 11.424×10^6 joules.
$\eta = 41\%$

11.12. $Q = 35.36$ MJ, $\eta = 32.7\%$

11.13. (a) 1.92×10^{-3} m^3/s, (b) 51.5%

11.14. From (11.5), $\eta_{\text{c}} = 45.1\%$
Now if $T_c = T_a$ the apparent efficiency is 78%.
But if $T_c = T_a$ there is no temperature rise and the actual efficiency is zero.

11.15. S facing roof, inclined at 54° to horizontal, 1 m^2/person of collector ≡ 4 m^2
10 gal/person storage ≡ 40 gallon tank
Cost ≈ £3200 + 20–25% if borrowed
or ≈ £3200 + 10–15% if loss of existing capital.
Electricity cost in UK (2002) is 7 p/kWh.
Lifetime of system (assuming proper maintenance) is about 20 years.

  (i) For a heavy user of water, annual saving on electricity bill might be £300. Payback period ≈ 10 years.
  (ii) For a light user of water, annual saving on electricity bill might be £100. Payback period ≈ £3200/100 ≈ 30 years, which exceeds the expected plant lifetime.

11.16. In northern Europe: average insolation = 100 W/m^2, with 3:1 energy input split between summer and winter. Cold ambient temperature in winter. Solar energy input is in time antiphase with the energy demand.
In the Middle East: average insolation = 300 W/m^2 with 1.5:1 split between summer and winter. Warm ambient temperature is winter. Solar energy input is in time phase with the refrigeration and air conditioning load. The chief obstacle to solar energy use is the cheap price of oil, especially in the Arab countries.

11.17. Carnot (heat → work) efficiency is greatly dependent on (and varies directly with) the working fluid temperature.
The working fluid is often required to be gaseous (e.g. steam).

11.18. $\eta_{\text{Carn}} = 410/723 = 56.7\%$

11.19. Low Carnot ideal efficiency = 20/293 = 6.83%

11.20.

$$\eta_{\text{Carn}} = \frac{T_{\text{fluid}} - T_{\text{amb}}}{T_{\text{fluid}}}$$

Let T_{fluid} increase to $(T+\Delta)_{\text{fluid}}$. Is, then,

$$\frac{(T+\Delta)_{\text{fluid}} - T_{\text{amb}}}{(T+\Delta)_{\text{fluid}}} > \frac{T_{\text{fluid}} - T_{\text{amb}}}{T_{\text{fluid}}}?$$

11.21. Combine η_{c} with η_{Carn}. Differentiate $\eta_{\text{c}}\eta_{\text{Carn}}$ and equate to zero to give QED solution.

$\eta_{\text{Carn}} = 0.424$, $\eta_{\text{c}} = 0.381$, $\eta_{\text{syst}} = 16.15\%$

11.22. See Eq. (11.6)

Heat losses in absorber $\propto T^4$

For flat-plate collector $CR = 1$

11.23. From (11.9),

$P \propto A$, $P \propto I_D$, $P \propto \eta_t$, $P \propto \eta_{\text{Carn}}$

11.24. Re-radiated power = 26 W/m^2 = 13%

11.25. $A_H = 0.471$ km^2, $A = 1.88$ km^2

11.26. Advantages:

- free fuel
- large construction project — jobs
- diversifies the sources of energy supply
- encourages new technologies

Disadvantages:

- large land area required
- large first cost (materials)
- pollution of manufacturing the materials
- destroys several square miles of animal habitat
- modification of hydrological cycle due to heliostat canopies
- modification of wind and water erosion due to site plus access roads

11.27. 37.65 km^2 or 14.54 square miles

11.28. One can devise any number of examples that incorporate the same arguments. For example, can a homeowner permit one of his trees to grow such that it will gradually shade the solar collector of a neighbour? Would it be reasonable or unreasonable to seek to go to law over such an issue? What is reasonable?

If a case arises such that the actions of one person prevent access to sunlight by another person, is this an infringement of legal right, moral right, good neighbourliness, reasonable behaviour, professional conduct, etc.? The issue is not merely academic. In order to reach solar collectors the radiation often has to pass through air space not owned or controlled by the solar collector site owner. It would seem prudent on the part of someone intending to install solar collecting equipment to ensure that the necessary intervening air space would not be subsequently blocked by the actions of other people.

There is no law in Western Europe or North America that at present (2002) covers the above eventualities.

Chapter 12

12.1. See the listing in Sec. 12.1.
12.2. Structure of silicon — Fig. 12.3 (a).
Covalent bonding — Fig. 12.4.
12.3. (a) Monocrystalline (sing1e crystal) — Sec. 12.4.1
(b) Polycrystalline — Sec. 12.4.1
(c) Amorphous — Sec. 12.4.2

12.4. "*n*-type" silicon is doped with an element containing five electrons — this increases the density of free electrons in the conduction band.
"*p*-type" silicon is doped with an element containing three electrons — this decreases the density of free electrons (increases the "holes") in the conduction band.
12.5. 1.08 eV or 2.63×10^{-19} joules
This energy corresponds to $f = 2.59 \times 10^{-14}$ Hz,
$\lambda = 1.15\ \mu$m, $c = 2.98 \times 10^8$ m/s.
12.6. The fraction of the solar spectrum that causes electrons to cross the energy gap decreases as the gap energy increases.
12.7. Increased working temperature causes increased thermal agitation of the lattice electrons. External radiation has fewer free electrons to dislodge and harvest, causing reduced current and reduced output power.
12.8. High purity material;
slow growth rate of crystal formation;
high waste factor by diamond slitting process;
labour-intensive fabrication.
12.9. No need to slice it into thin wafers (minimises waste).
12.10. More expensive than silicon;
raw material stock inadequate for mass production.
12.11. Much easier (and cheaper) to form into cell wafers.
12.12. Upper wavelengths of the solar spectrum will not produce free electrons and low wavelengths have only limited capacity to produce free electrons; junction temperature losses; cell material temperature losses.
12.13. Reduces the necessary amount of (expensive) solar cell material.
12.14. Increase of temperature causes significant decrease of efficiency — forced cooling is needed in some applications.
12.15. (a) In space the exposure is for 24 hours, compared with (say) 12 hours on earth.
(b) In space the insolation is four times the value at the earth surface.

In combination (a) and (b) reduce the necessary area in space, compared with earth, by a factor of $2 \times 4 = 8$.
12.16. See Fig. 12.8.

12.17. See Figs. 12.8 and 12.9.
By iteration (trial and error) taking the current–voltage product for each co-ordinate.

12.18. $V_{mp}/V_{oc} \approx 0.8$, $I_{mp}/I_{sc} \approx 0.9$

12.19. (i) $I_{sc} = \frac{850}{1000} \times 1.5 = 1.275$ A, (ii) $I_{sc} = \frac{300}{1000} \times 1.5 = 0.45$ A

12.20.

	1000 W/m^2		500 W/m^2	
load resistance	8 Ω	20 Ω	8 Ω	20 Ω
voltage current (mA)	0.386 49	0.525 26	0.21 26	0.46 23

12.21. −0.72 V/10°C, 4%

12.22. The short circuit current I_{sc} is almost directly proportional to the incident radiation.

12.23. The equivalent circuit has the form of Fig. 12.11 (b). For 500 W/m^2, $I_s =$ 2.75 mA.
At the maximum power point P_n, $V = 0.43$ V and $I = 25$ mA, $R_0 = (0.43 \times 1000)/25 = 17.2\Omega$. $I_j = 27.5 - 25 = 2.5$ mA, $R_j = (0.43 \times 1000)/2.5 = 172\Omega$.

12.24. At 1000 W/m^2, $I_s = 50$ mA.

R_0 (ohms)	V (V)	I (mA)	I_j (mA)	$V/I_j = R_j$
5	0.26	49.5	0.5	520
10	0.46	45	5	92
50	0.54	11.5	38.5	14

Variation of R_j with current is shown in Fig. P.12.24, in which the bend of the curve follows the knee of the current–voltage characteristic.

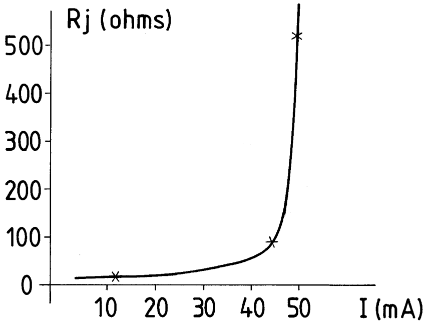

Fig. P.12.24. Solution of problem 12.24.

12.25. For the 5 Ω characteristic in Fig. 12.24:

Insolation	V (V)	I (mA)	I_s (mA)	I_j (mA)	R_j (Ω)
1000 W/m^2	0.26	49.5	50	0.5	520
500 W/m^2	0.14	37	27.5	22.5	6.22

12.26. $R_L = V_m/I_m = 0.44/57.5/1000 = 7.65\ \Omega$
12.27. $R_L = 0.425/36/1000 = 16.25\ \Omega$
12.28. I_{sc} is double and V_{oc} is tripled, compared with a single cell.
12.29. I_{sc} is tripled and V_{oc} is doubled, compared with a single cell.
12.30. (i) At 1000 W/m^2, $I_s = 50$ mA
With $R_0 = 10\ \Omega$, $V = 0.46$ V and $I = 45$ mA/cell.
With n cells in parallel:

$$I = n(I_s - I_j) = nI = 20 \times 45/100 = 0.9\ \text{A}$$
$$P_0 = VI = 0.46 \times 0.9 = 0.414\ \text{W}$$

(ii) At 500 W/m^2, $I_s = 27.5$ mA
With $R_0 = 10\ \Omega$, $V = 0.27$ V, $I = 27$ mA/cell
With 20 cells in parallel:

$$V = 0.27\ \text{V},\ I = 20 \times 27/1000 = 0.54\ \text{A}$$
$$P_0 = 0.27 \times 0.54 = 0.15\ \text{W}$$

By connecting 20–25 cells in series.
At 1000 W/m^2 and $R_0 = 10\Omega$, $V = 0.46$ V/cell
$I = 45$ mA/cell
12.31. With 100 cells in series $V = 100 \times 0.46 = 46$ V
12.32. $I = 45$ mA, $P = 46 \times 45/1000 = 2.07$ W

Chapter 13

13.1. Competition with food production
Change of water and nutrient demand
Effect on wildlife
Contamination of local food crops
13.2. See Sec. 13.2.
Solar radiation → stored chemical energy
13.3. See Sec. 13.2 and Table 13.1
Temperate: 0.5–1.3%
Tropical: 0.5–2.3%
Average ≈ 1%

13.4. See Sec. 13.2
Temperate 0.5–1.3%
Tropical 0.5–2.3%
13.5. Rapeseed — a biofuel plant
13.6. Methane
Abundance of human and animal dung for fuel
Need for cooking fuel
13.7. Widespread growth, ease of intensive farming, combustibility of forestry products, less polluting than coal or oil, carbon-dioxide-neutral.
13.8. Carbon dioxide given up on combustion is the same amount as the carbon dioxide absorbed in photosynthetic growth.
13.9. High calorific value (37 MJ/kg) but releases toxic fumes.
13.10. More rapeseed (bright yellow) and linseed (blue). Fewer conventional food crops. More arable coppice plantation of small (up to 3 ft) trees.
13.11. No plastic. Less paper and packaging. Less food waste. More glass (?). More ash and cinders.

13.12. from Table 13.9

	1990	2000
(a)	7.2%	24.4%
(b)	15.8%	16.8%
(c)	14.5%	21.2%

13.13. (a) Wood and waste increased by 13.2% of the 1999 figure
(b) Hydropower increased by 12.2% of the 1999 figure
(c) Solar power increased by 22.4% of the 1999 figure
(d) Wind power increased by 36.8% of the 1999 figure

13.14. Comparing Tables 13.6 and 13.7:

	UK	USA
Paper and cardboard	30.5%	38.1%
Food waste	24%	10.9%
Glass	11.2%	5.5%
Rubber leather & textiles	13.2%	6.6%

13.15. 28 Mtonnes yields a gross 3×10^{12} MJ.

$$\begin{aligned}\text{At 50\% efficiency} &= 1.5 \times 10^{12}\ \text{MJ}\\ &= 1.5 \times 10^{12}/3.6 = 0.417 \times 10^{12}\ \text{kWh}\end{aligned}$$

13.16. $28 \times 10^6 \times 5000/3.6 = 38.9 \times 10^9$ kWh
13.17. Reduced dependence on oil
Reduced emissions

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